Technically and Economically Viable Future Electricity and Fuel Storage Technologies

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Abstract

Due to rapid growth in global energy demand, as well as intermittency characteristics of renewable sources, and fluctuation in energy demand and supply, energy storage technologies are one of the most crucial solutions for the future. This study analyzes several storage technologies in terms of technical and economical viability perspectives, with projections for the near future (up to 2050). Literature surveys, qualitative discussions, and mathematical models are incorporated into the analyses. The working principles of several storage technologies, together with their advantages and disadvantages, are highlighted. This is followed by an in-depth qualitative analysis of technical characteristics. Based on levelized cost of storage models, lithium-ion battery has a significant cost advantage, despite the cost reductions that pumped hydro storage and compressed air energy storage might undergo. Hydrogen storage and some developing technologies such as flow batteries and liquid air energy storage are not yet close to being cost competitive with lithium-ion battery. Additionally, sensitivity analyses were created for two technologies which were addressed with special attention in the energy market, namely lithium-ion battery and hydrogen storage. Sensitivity analyses were constructed based on different variables such as round trip efficiency, lifetime, and annual production, among others. Further analysis regarding sustainability implies that cobalt scarcity will occur after 2042 for lithium-ion batteries. Finally, security/scalability problems for hydrogen storage and the factors slowing down the commercialization of fuel cell technology are underlined.

Keywords Battery, Energy Storage Technologies, Fuel Cell, Hydrogen Storage, Levelized Cost of Storage, Lithium-ion Battery

Preface

This study has been a truly memorable journey with the support of amazing people around me. First and foremost, I would like to express my most special gratitude to my supervisor Professor Ilkka Kauranen. I am grateful for his continuous guidance and valuable comments. I appreciate his generosity for spending exceptional amount of time and communicating profound feedback with patience in order to improve this study.

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In addition, I would like to thank all my instructors at Aalto University and Bogazici University for their extensive contribution to my life. Also, I appreciate the encouragement of my friends from Turkey and Finland. I am really lucky to have such great people in my life. Last but not the least, I am extremely grateful for having an amazing family who has always given me their endless support and raised me with true love.

Finally, there are also some personal motivation points which have encouraged me to write about this study. First of all, energy storage is a highly relevant concept for our world that will shape the future of energy sector. In order to get a solid grasp on this concept, it is extremely important to gain overall knowledge about the existing and expected technologies. Secondly, providing a concise study by tackling the desired topic from various angles adds a great academic value to the community which has interest on the subject. Last but not the least, raising the awareness about environmentally friendly and sustainable solutions for storing excess energy is one of the most critical motivations of this study. With all these points, I hope this study will encourage all relevant companies and individuals to support the improvements in energy storage technologies and to contribute to the transition into a sustainable future.

Otaniemi, August 28, 2019

Emre Korkmaz

Contents

Abstract 3

Preface 4

Contents 5

Symbols and abbreviations 9

1 Introduction 11
- 1.1 Background . . . 11
- 1.2 Motivation . . . 12
- 1.3 Objective of the study . . . 12
- 1.4 Research methods . . . 13
- 1.5 Technical definitions . . . 13
- 1.6 Structure of the study . . . 15

2 Classification of energy storage technologies 17

3 Description of storage technologies 18
- 3.1 Pumped hydro storage (PHS) . . . 19
- 3.2 Compressed air energy storage (CAES) . . . 20
- 3.3 Liquid air energy storage (LAES) . . . 21
- 3.4 Lead-acid battery (LAB) . . . 22
- 3.5 Sodium sulphur (NaS) battery . . . 23
- 3.6 Flow batteries . . . 24
  - 3.6.1 Vanadium redox flow battery (VRFB) . . . 25
  - 3.6.2 Polysulfide bromide (PSB) flow battery . . . 25
- 3.7 Nickel-cadmium (NiCd) battery . . . 26
- 3.8 Lithium-ion battery . . . 27
  - 3.8.1 Lithium cobalt oxide (LCO) . . . 28
  - 3.8.2 Lithium manganese oxide (LMO) . . . 28
  - 3.8.3 Lithium iron phosphate (LFP) . . . 28
  - 3.8.4 Lithium nickel cobalt aluminium oxide (NCA) . . . 28
  - 3.8.5 Lithium nickel manganese cobalt oxide (NMC) . . . 28
- 3.9 Supercapacitors . . . 30
- 3.10 Superconducting magnetic energy storage (SMES) . . . 31
- 3.11 Hydrogen storage and fuel cells . . . 32

4 Comparing technical characteristics of storage technologies 33
- 4.1 Primary technical properties . . . 33
- 4.2 Secondary technical properties . . . 41

5 Levelized cost of storage (LCOS) model overview 43
5.1 Lithium-ion battery 45
5.2 Hydrogen storage 48
5.3 Remaining storage technologies 54

6 Selecting technologies for further analyses 58

7 Sensitivity analyses 59
7.1 Lithium-ion battery 59
7.2 Hydrogen storage 65

8 Sustainability and commercialization analyses 68
8.1 Lithium ion battery 68
8.1.1 Material availability 68
8.1.2 Energy density improvements 75
8.1.3 Recycling 75
8.2 Hydrogen storage 78
8.3 Fuel cells 79

9 Reliability and validity analysis 81

10 Conclusions 82

11 Recommendations for future studies 84

References 85

A Material availability calculations for 2020, 2030, and 2050 90

B Levelized cost of storage calculations for 10 other technologies (low decrease scenario) 93

List of Figures

1 Energy storage diagram . . . 17
2 Classification of energy storage technologies . . . 18
3 Pumped hydro storage system . . . 19
4 Structure of compressed air energy storage: a) diabatic CAES and b) adiabatic CAES . . . 20
5 Structure of liquid air energy storage . . . 21
6 Structure of lead-acid battery . . . 22
7 Structure of sodium sulphur battery . . . 23
8 Structure of flow battery . . . 24
9 Structure of a nickel cadmium battery . . . 26
10 Structure of lithium-ion battery . . . 27
11 Structure of supercapacitor . . . 30
12 Structure of superconducting magnetic energy storage . . . 31
13 Structure of hydrogen storage and fuel cell . . . 32
14 Critical self-discharge rates and suitable energy shifting timeline . . . 35
15 Maturity of storage technologies . . . 38
16 Energy and power capital cost of energy storage technologies . . . 40
17 Applications based on discharge time . . . 41
18 Technical characteristics of storage technologies . . . 42
19 Expected annual lithium-ion battery capital costs (C-rate 0.25) . . . 45
20 Levelized cost of storage (LCOS) for 3 different cost decrease scenarios - Lithium-ion battery . . . 46
21 Levelized cost of storage (low decrease scenario) - Lithium-ion battery 47
22 Hydrogen storage overall levelized cost of storage (LCOS) from 2020 to 2050 . . . 50
23 Levelized cost of hydrogen storage (production, storage, and utilization) 53
24 Levelized cost of storage for three different capital cost decrease scenarios for ten technologies . . . 55
25 Sensitivity analysis with two variables for lithium-ion battery: round trip efficiency and annual charging times . . . 60
26 Sensitivity analysis graphs for lithium-ion battery: a)round trip efficiency and b) annual charging times . . . 61
27 Sensitivity analysis with two variables for lithium-ion battery: lifetime and storage capital expenditures (capex) . . . 63
28 Sensitivity analysis graphs for lithium-ion battery: a) lifetime and b) storage capex . . . 64
29 Sensitivity analysis with two variables for hydrogen storage: electricity price and annual production . . . 66
30 Sensitivity analysis graph for hydrogen storage (annual production) . 67
31 Metal contents of different lithium-ion battery chemistries . . . 68
32 Expected annual lithium-ion battery demand . . . 69

33 Compound annual growth rate (CAGR) values and data projection: a) forecasted lithium-ion battery demand, b) compound annual growth rate (CAGR) values, and c) projected lithium-ion battery demand . . 70
34 Lithium-ion battery demand and share for each category for years 2020, 2030, 2040, 2050: a) Lithium-ion battery demand and b) share for each category 71
35 Battery chemistry mix: a) passenger electric vehicles (EVs) and b) stationary storage 72
36 Material availability calculations for 2040 74
37 Lithium-ion battery (LIB) recycling data: a) lithium-ion battery (LIB) waste data and b) data for existing recycling facilities 76
38 Economics of lithium-ion battery recycling 77

Symbols and abbreviations

Symbols

Al	Aluminium
C	Carbon (Natural graphite)
Co	Cobalt
Cu	Copper
Fe	Iron
GWh	Gigawatt hour
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt hour
L	Liter
MJ	Megajoule
Mn	Manganese
MPa	Megapascal
MW	Megawatt
MWh	Megawatt hour
Li	Lithium
Na	Sodium
Ni	Nickel
$Ni(OH)_2$	Nickel hydroxide
P	Phosphorus
Pb	Lead
PbO_2	Lead oxide
Ti	Titanium
USD	US dollar
V	Vanadium
W	Watt
Wh	Watt hour

Abbreviations

AA-CAES	Advanced Adiabatic Compressed Air Energy Storage
AC	Alternating Current
BOP	Balance of Plant
CAES	Compressed Air Energy Storage
CAGR	Compound Annual Growth Rate
Capex	Capital Expenditures
CES	Cryogenic Energy Storage
DC	Direct Current
D-CAES	Diabatic Compressed Air Energy Storage
DOD	Depth of Discharge
EPC	Engineering, Procurement, and Construction
E–busses	Electric Busses
ESS	Energy Storage System
EV	Electric Vehicle
FOM	Fixed Operation and Maintenance
LAB	Lead Acid Battery
LAES	Liquid Air Energy Storage
LCO	Lithium Cobalt Oxide
LCOP	Levelized Cost of Production
LCOS	Levelized Cost of Storage
LFP	Lithium Iron Phosphate
LIB	Lithium-ion Battery
Li–ion	Lithium–ion
LMO	Lithium Manganese Oxide
NaS	Sodium Sulphur
NCA	Lithium Nickel Cobalt Aluminium Oxide
NiCd	Nickel Cadmium
NMC	Lithium Nickel Manganese Cobalt Oxide
O&M	Operation and Maintenance
PCS	Power Conversion System
PEM	Proton Exchange Membrane
PHS	Pumped Hydro Storage
PSB	Polysulfide Bromide
Redox	Oxidation and Reduction
SMES	Superconducting Magnetic Energy Storage
TRL	Technology Readiness Level
VRFB	Vanadium Redox Flow Battery
WACC	Weighted Average Cost of Capital

1 Introduction

1.1 Background

Storing surplus energy has a great importance for our world since non-renewable resources are scarce and renewable resources are intermittent. The demand for energy is also fluctuating during a day or between the seasons. When storing excess energy, it is critical to choose technically and economically viable solutions. Comparing different storage technologies and identifying the most promising ones create an attractive business opportunity for relevant companies. This process also requires broad research and financial investment from companies' side.

Available literature has covered many different aspects of various storage technologies, from creating an overview about their technical characteristics and identifying suitable applications for them, to assessing their economic and environmental impact. Akinyele et al. [1], Luo et al. [37], and Ferreira et al. [20] are some of the studies in which the subject of energy storage is treated comprehensively. In all three studies, many different storage technologies are examined together with their suitable application areas, and their technical features are summarized. In another study, Zakeri et al. [63] also provide information regarding technical characteristics about several storage technologies. However, their study's focus is mainly in the direction of comparing capital costs and life cycle costs of their selected technologies.

In terms of cost of storage specifically, there are also many studies tackling the problem from slightly different perspectives. These studies differ in the number of technologies discussed, the application areas of technologies considered, and the general approach to the topic, be it more theory or data based. Julch [29] assesses levelized cost of storage for four different technology groups by using real input data. There is comprehensive financial and technical data collected and applied into the analysis. She enriches her study by providing a broad view on cost components as well as conducting sensitivity analyses for key input data. On the other hand, Belderbos et al. [5] approach the topic more theoretically. They focus on profitability of storage technologies by analysing the impact of different cost metrics. Finally, Schmidt et al. [49] study levelized cost of storage for specific applications for many technologies. They also project the cost results for each application while estimating the probability of each technology's potential of having the lowest cost within its assigned application group.

Additionally, there are some studies investigating material availability for lithium-ion battery. However, the number of these studies is much less compared to the cost and technical features related studies. Particularly, there is a well-structured study written by Olivetti et al. [44] which is concentrating on the demand and supply of critical materials for lithium-ion battery, especially cobalt. There is also a discussion part about recycling and development of new technologies.

1.2 Motivation

The necessity for technically and economically viable energy storage technologies is becoming more important due to significant growth in surplus renewable energy, inconsistent fluctuation between energy supply and demand, expansion in electric vehicle market, and increase in electrification of some large scale sectors like heating and cooling. Globally, variable renewable energy generation is expected to rise, and energy storage is going to be a potential solution to bridge the gap between supply and demand. This will also help dealing with the problem of curtailment by providing higher efficiency and flexibility for power system operators. Additionally, energy storage technologies will reduce the reliance on fossil fuels, therefore carbon dioxide emissions stemming from industries that are highly dependent on fossil fuels will decrease. [19]

Wärtsilä Energy Business (the business unit of the target company of this study) is providing hybrid power plant solutions by incorporating storage capacity for different applications such as spinning reserve, power quality, and ancillary services. Since energy storage is a part of Wärtsilä's business and the concept of storage in energy industry will get more attention in the near future, the target company seeks for a better understanding of economically and technically viable storage technologies. The levelized cost of storage, technical characteristics of several technologies, and sustainability analyses for lithium-ion battery and hydrogen storage are central focus areas of the company in this regard. Lithium-ion battery and hydrogen storage (including fuel cell) have been particularly selected for further analyses by the company. These analyses cover the sensitivity analyses of levelized cost and sustainability related matters like material availability and commercialization. This study helps the company to see the real business value of the selected storage technologies by comprehensively presenting many important factors from different perspectives.

1.3 Objective of the study

The objective of this study is to improve the understanding of the target company about the technical and economic viability of different energy storage technologies from the viewpoint of their value for the energy sector in the future until the year 2050.

When studying different energy storage technologies, this study focuses on technical and economical viability. These properties are partly complementary. This study uses parallel analyses which increase the reliability, validity, and comprehensiveness of the results. A generic financial model is created to calculate and project the Levelized Cost of Storage (LCOS) for each technology. Levelized cost of storage is defined as the total lifetime cost of an investment divided by the aggregate energy generated from this investment [46]. Sustainability matters are also studied with emphasis on scalability and commercialization [27]. The subjects of resource availability and recycling are highlighted. This study is assessing how realistic it is to invest in various energy storage technologies. Scientifically, the study contributes with its thoroughly collected data, multiple qualitative and quantitative analyses created with novelty, and the broadness of the scope covered within the same study.

1.4 Research methods

This study has been constructed based on a combination of several research methods. Those methods include literature survey, qualitative discussion, deductive approach, and creation of mathematical models.

For such a broad study incorporating different aspects of several technologies, literature survey contributes essentially. Literature survey is used in order to learn the definitions of technical terms, gain understanding of the working principles of selected storage technologies, and access the most up to date data. Literature survey also provides grounds for qualitative discussions, where data and findings are interpreted and correlated using logical reasoning.

The mathematical models include sensitivity analyses, levelized cost of storage calculations, material availability analyses and recycling value analyses. The models allow conclusions to be drawn from real collected data, combined with realistic assumptions. The models and calculations help come up with reasonable conclusions and comparisons. Figures are also obtained from the models, which provide valuable visual representations. Finally, deductive approach has been employed in order to test the existing theory of material scarcity for lithium-ion battery. In order to initiate a deductive approach, these steps should be followed respectively: having an existing theory, defining a hypothesis based on that theory, testing the hypothesis by collecting relevant data, and checking if the hypothesis is validated or denied [54].

1.5 Technical definitions

This section provides definitions of key terms which will be used throughout this study and are vital for the subsequent analysis.

C-rate: "*A charge rate that, under ideal conditions, is equal to the energy storage capacity of an electricity storage device divided by 1 hour. 1 C is the charge rate necessary to charge a battery in one hour. 10 C charges in 6 minutes and 0.1 C charges in 10 hours*" [17].

Cycle efficiency (round trip efficiency): "*Cycle efficiency, also named the round trip efficiency, is the ratio of the whole system electricity output to the electricity input*" [37].

Depth of discharge (DOD): Depth of discharge (DOD) "*expresses how much of the stored energy in a device has been used*" [22]. For instance, a fully charged battery would have 0% depth of discharge while an empty battery is having 100%. Moreover, high depth of discharge values cause shorter lifetimes [22].

Discharge efficiency: "*Discharge efficiency represents the energy transmission ability from the energy-storing phase to the energy-releasing phase, which contributes to the overall cycle efficiency achieved*" [37].

Energy capital cost: "*Energy related costs include all the costs undertaken to build energy storage banks or reservoirs, expressed per unit of stored or delivered energy*" [63].

Energy density: "*The energy density is calculated as a stored energy divided by the volume*" [10]. Volume refers to the whole energy storage system's volume which includes the possible inverter system, storage part and supporting structures [10].

Lifetime: "*This parameter refers to the number of charge-discharge cycles that the system can handle without considerably losing its power, energy and efficiency capabilities*" [2]. Since mechanical storage technologies are less temperature-dependent and are less affected by chemical deterioration compared to other storage systems, they are prone to have longer lifetimes [2].

Load following: "*Load following manages system fluctuations on a time frame that can range from 15 minutes to 24 hours, and can be controlled through automatic generation control, or manually*" [36].

Maturity: "*The maturity is referred to the experience acquired in the use of a specific technology, to the level of commercialization, the technical risks and the related economic benefits*" [2].

Operation and maintenance (O&M) costs: "*The operating cost covers the cost of operation, maintenance, disposal and replacement*" [3].

Peak shaving: "*Peak shaving means using energy stored at off-peak periods to compensate electrical power generation during periods of maximum power demand*" [37].

Power capital cost: Power capital cost refers to the cost of the power conversion system (PCS) and is generally defined in terms of per unit of power capacity [63].

Power density: "*The power density (W/kg or W/litre) is the rated output power divided by the volume of the storage device*" [10]. Volume refers to the whole energy storage system's volume which includes the possible inverter system, storage part and supporting structures [10].

Power quality: "*Power quality provides electrical service to customers without any secondary oscillations or disruptions to the electricity 'waveform' such as swells/sags, spikes, or harmonics*" [10]. It has high operational significance for power systems in order to produce accurate power and deliver consumers at adequate voltage levels [1].

Power rating: "*The power rating represents the maximum power that the system can handle during the charge and discharge phases, while the energy is often associated to the system capacity*" [2].

Response time: Response time refers to the release speed of the stored energy. Response time can be a critical limitation while deciding the application area. For instance, voltage drop and flicker mitigations need milliseconds as response time. [3]

Self-discharge: "*Self-discharge is related to energy dissipation, in the forms of heat transfer losses in thermal storage, air leakage losses in compressed air storage, electrochemical losses in batteries, etc.*" [37].

Specific energy: Specific energy indicates the total energy per unit weight [37].

Specific power: Specific power indicates the total power per unit weight [37]. In order to reduce the weight of an energy storage system (ESS) (while obtaining a particular amount of energy), specific energy and specific power should be increased [37].

Spinning reserve: "*Spinning reserve is the power generation capacity which can be activated on decision of the system operator and which is provided by devices that are synchronized to the grid and able to affect the active power*" [21].

Storage duration: Storage duration "*shows how much of the stored energy can be retained by the energy storage device for over a period of time*" [3]. Storage duration has direct relation with self-discharge rate i.e. long duration storage requires low self-discharge rate [3].

Time shifting: "*Time shifting can be achieved by storing electrical energy when it is less expensive and then using or selling the stored energy during peak demand periods*" [37].

1.6 Structure of the study

This study is organized as eleven chapters:

- **Chapter 1: Introduction.** This chapter includes a background highlighting some of the existing research on energy storage technologies. It then provides the motivation and objective of the study, as well as the applied research methods. This chapter is finalized by providing the definitions of the most essential technical terms.
- **Chapter 2: Classification of energy storage technologies.** In this chapter, the energy storage concept is briefly explained. Storage technologies within

this study are classified under relevant categories.

- **Chapter 3: Description of storage technologies.** This chapter consists of the general descriptions of the selected technologies as well as a summary of their advantages and disadvantages.
- **Chapter 4: Comparing technical characteristics of storage technologies.** Technical characteristics are emphasized and compared.
- **Chapter 5: Levelized cost of storage (LCOS) model overview.** Levelized cost of storage models are explained. Special attention is given to lithium-ion battery and hydrogen storage. The results are interpreted and compared.
- **Chapter 6: Selecting technologies for further analyses.** A justification is given regarding why lithium-ion battery and hydrogen storage in particular are selected for further analyses.
- **Chapter 7: Sensitivity analyses.** Sensitivity analyses for lithium-ion battery and hydrogen storage are conducted in order to measure the impacts of certain variables.
- **Chapter 8: Sustainability and commercialization analyses.** A material availability model is created to identify critical materials for lithium-ion battery. Alternative technologies and materials (for lithium-ion battery) have been discussed. Recycling value of lithium batteries is also estimated with a structured model. Additionally, hydrogen storage, together with fuel cells, are assessed in terms of safety and scalability.
- **Chapter 9: Reliability and validity analysis.** The reliability and validity of the study is evaluated.
- **Chapter 10: Conclusions.** Important findings of the study are summarized and overall idea of the study is recaptured.
- **Chapter 11: Recommendations for future studies.** Suggestions are made for the sake of future research.

2 Classification of energy storage technologies

Before attempting to categorize storage technologies, it is critical to gain a deeper understanding of the general storage concept. The idea of energy storage is defined as capturing energy and storing it with different methods or materials to use at another time [3]. Figure 1 presents the generic flow diagram for the energy storage concept. As shown in the figure, electricity is both input and output of the system. Charging and discharging phases are usually represented as capturing and releasing the energy respectively [3]. During this process, the system has potential for losses due to for example conversions or leakages. Additionally, storage systems have a round trip efficiency which is calculated by using charging efficiency, discharging efficiency and self-discharge.

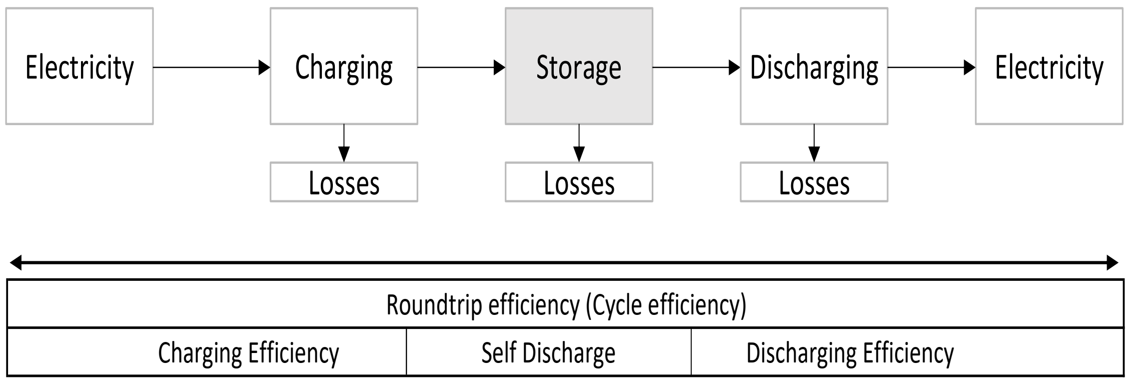


Figure 1: Energy storage diagram

This study focuses on storage technologies under four main categories: 1) Mechanical storage, 2) Electrochemical storage, 3) Electric and magnetic storage, and 4) Chemical storage. First group, mechanical storage, refers to a system where electricity is converted to kinetic or potential energy with the help of a mechanical process such as pumping, acceleration, compression etc. [22]. An electrochemical storage system consists of a reversible set of reactions, especially oxidation and reduction (redox), which allows energy to be stored in the form of chemical energy [22]. Based on the explanation of Gallo [22] according to Chen [10], in the electric and magnetic storage category, an electric or magnetic area is created in order to store energy as electric potential energy. Finally, chemical storage includes processes where energy is stored within the body of chemical compounds such as hydrogen and methane. This can provide high energy density [3]. In Figure 2, storage technologies that are within the scope of this study can be under the classification category they belong to. This classification chart gives an overall understanding before getting into the details of each individual technology.

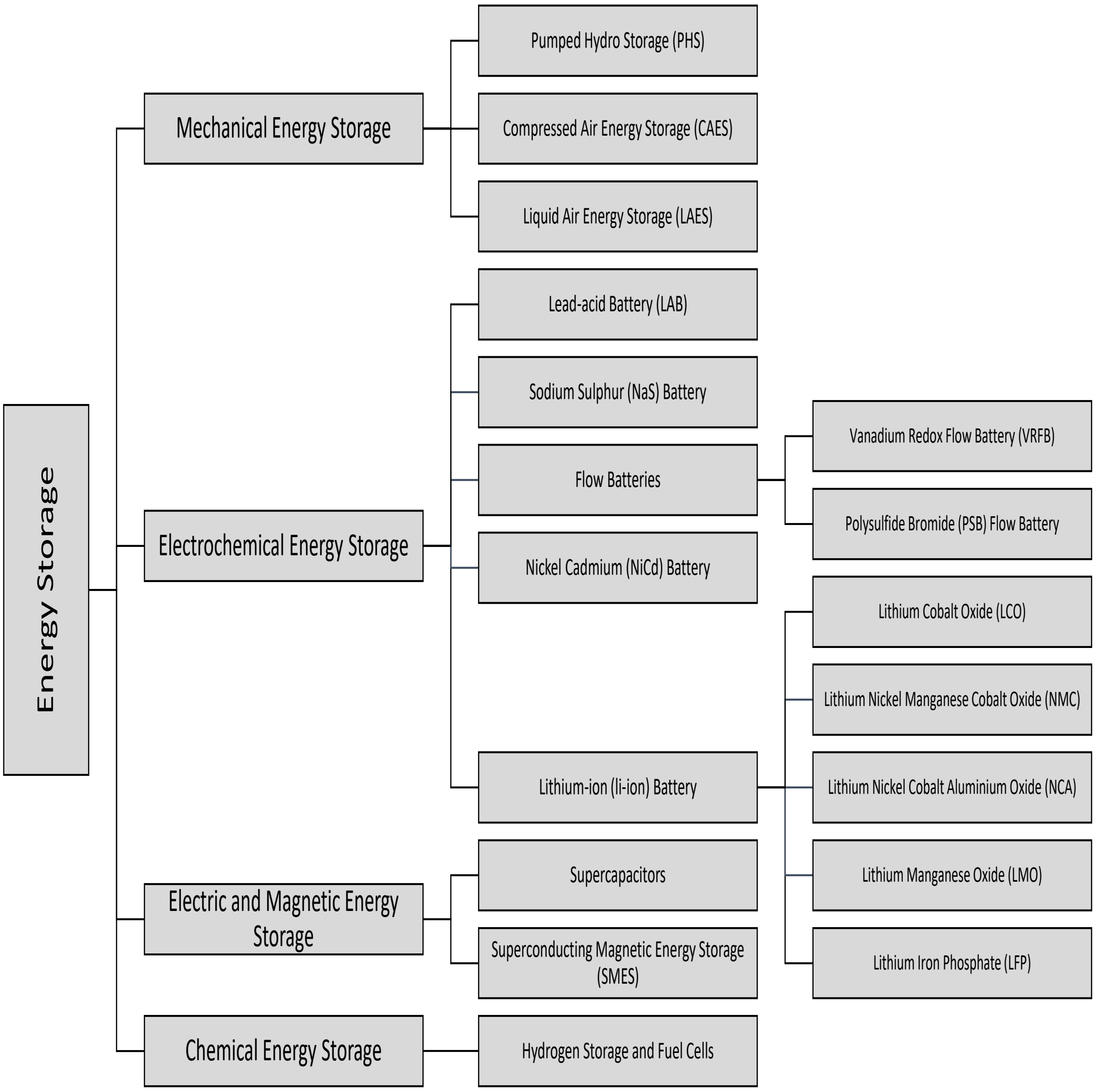


Figure 2: Classification of energy storage technologies, The figure is based on the data from different resources [3, 11, 22, 63]

3 Description of storage technologies

In this chapter, the working principles of the selected storage technologies will be introduced, followed by some of the advantages and disadvantages of their technical and commercial features. This chapter will be kept qualitatively concise, and the details of the technical characteristics will instead be evaluated in Chapter 4.

3.1 Pumped hydro storage (PHS)

During low demand hours, a pumped hydro storage system utilizes electricity in order to pump the water from a lower reservoir to a higher one. This energy which is stored in the form of potential energy can then be used during any high demand hours by allowing the water flow in the reverse direction. The storage process, which is the charging phase, is managed by a pumping motor, while the electricity generation process, which is the discharging phase, is achieved by a turbine. Flow of the water in both directions is controlled by a valve. A typical diagram for a pumped hydro storage system is presented in Figure 3. [3, 14, 37]

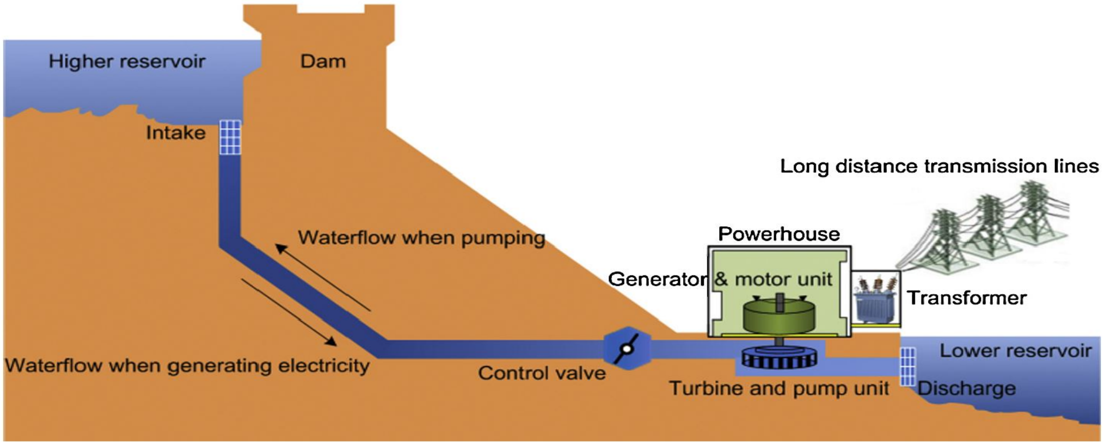


Figure 3: Pumped hydro storage system [37]

Some studies mention that pumped hydro storage is the most mature and commercially proven storage technology worldwide [22, 24, 63]. Aneke [3] and Zakeri [63] mentioned according to Electric Power Research Institute (EPRI) [18] that pumped hydro storage denotes 99% of the global installed storage capacity. Some of the most important advantages and drawbacks of the pumped hydro storage technology are:

- **Advantages:** Pumped hydro storage allows storage in large volumes with long storage duration, low storage costs, and very low self-discharge rate [27]. Moreover, it is a technically and commercially mature technology which has a quick response time, relatively low energy capital cost, and high efficiency [2].

- **Disadvantages:** Pumped hydro storage systems have high capital costs and it takes a long time to break even. Low energy density, long construction time, difficulties in finding a suitable place due to geographical restrictions, and environmental matters related to construction are other significant barriers of the technology. [27]

3.2 Compressed air energy storage (CAES)

In a (traditional) compressed air energy storage system, off-peak electricity is used to compress air in suitable reservoirs such as natural underground salt caverns. During the discharging phase, stored air is released and heated to increase power quality. The heating process takes place by means of either a fossil fuel driven combustion chamber, or by utilizing the heat generated during compression. A typical heating method is by combustion, in which case the system is called diabatic compressed air energy storage (D-CAES). Alternatively, if recovered heat is used for the expansion, the system is called advanced adiabatic compressed air energy storage (AA-CAES). The difference is illustrated in Figure 4. At the end of the process, the air is used by turbines to produce electricity. Recently, advanced adiabatic compressed air energy storage is gaining more attention than diabatic compressed air energy storage. This is due to emission related hazards of diabatic compressed air storage technology which occur during the combustion phase. [27, 37]

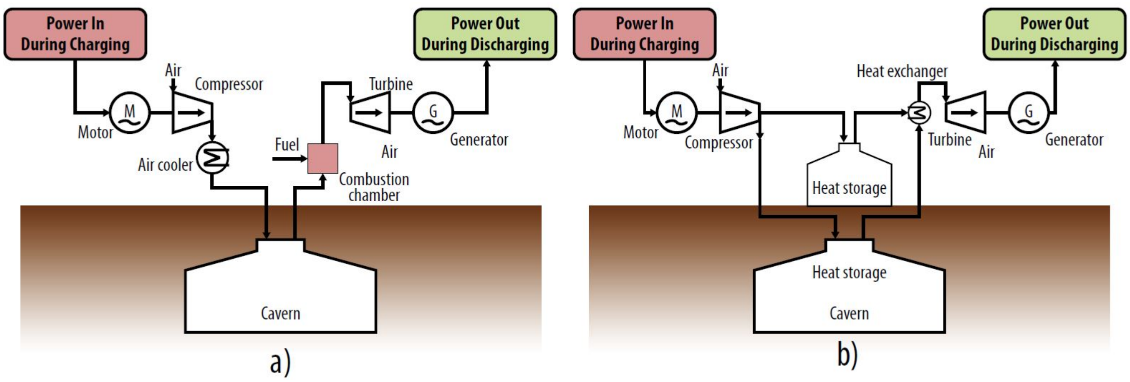


Figure 4: Structure of compressed air energy storage: a) diabatic CAES and b) adiabatic CAES [21]

Advanced adiabatic compressed air energy storage, in which the heat released from the compression is utilized without including any combustion mechanism [27], will not be covered under the scope of this study since it is not a topic of interest for the target company. Some positive and negative aspects for diabatic compressed air energy storage can be listed as the following.

- **Advantages:** Compressed air energy storage is a mature and commercially proven technology with large scale storage capacity and long lifetime. It requires low initial capital investments compared to pumped hydro storage. [22] Also, it can offer long storage duration [2].

- **Disadvantages:** Determining a convenient location and having low efficiency (around 42%) are major drawbacks of compressed air energy storage technology [37]. In addition, operational costs are high because of fuel consumption [22].

3.3 Liquid air energy storage (LAES)

Liquid air energy storage (LAES), which is recognized as cryogenic energy storage (CES) according to some sources [3, 34], is a recently developed technology in which energy is stored in the form of liquefied air [22]. As illustrated in Figure 5, at the first phase the air is compressed and liquefied with excess electricity. Liquid air is then stored at atmospheric pressure in insulated tanks. Finally, at the discharging stage, high-pressure liquid air is expanded in heat exchangers to generate electricity by passing through turbines. Additionally, waste heat and cold is also stored in separate tanks in order to be reused during the overall process. [3, 22, 34]

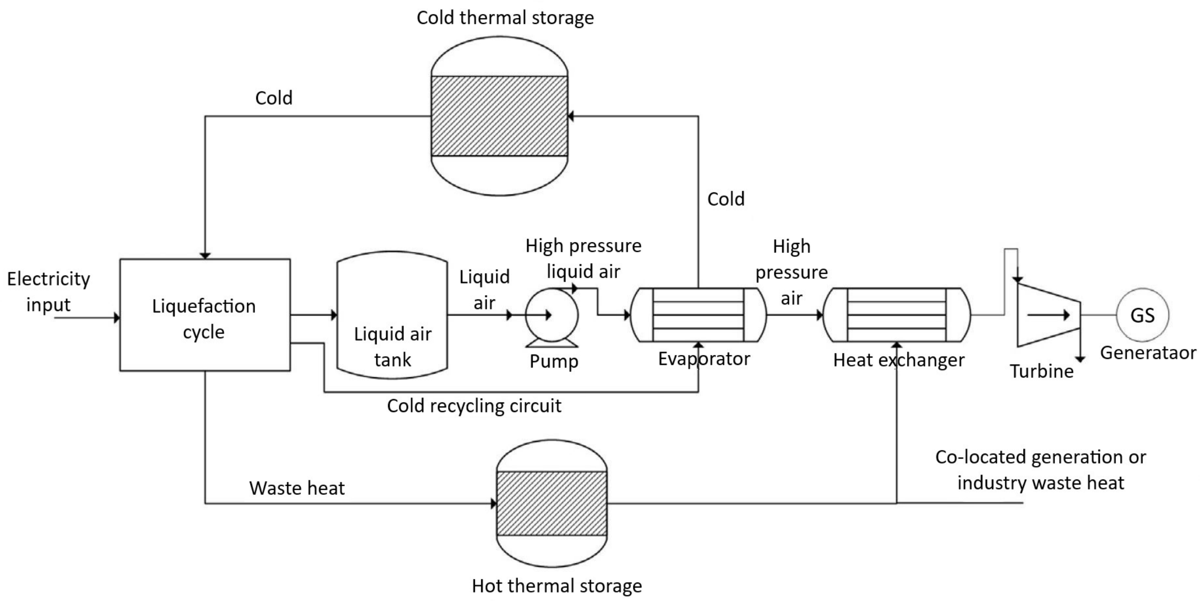


Figure 5: Structure of liquid air energy storage [22]

Some of the major advantages and disadvantages of liquid air energy storage are:

- **Advantages:** Gallo [22] highlights according to Stöver [53] that liquid air storage provides a better energy density value than a typical pumped hydro storage or a compressed air energy storage system. Also, liquid air storage technology has no restrictions in location nor land size. A liquid air storage plant is notably smaller compared to pumped hydro storage or compressed air energy storage. [22].
- **Disadvantages:** A major disadvantage of liquid air energy storage is the low efficiency of 40-50%. However, efficiency can be improved with the help of waste heat reuse to up to 75-85%. This situation requires sufficient storage and supply of the heat where it is generated within the system. Additionally, the high cost of liquefaction is also a downside of liquid air storage technology. [22]

3.4 Lead-acid battery (LAB)

As one of the most mature and widely applied battery technologies, a simple lead-acid battery layout contains cells connected in series in a medium where sulphuric acid (H_2SO_4) is used as the electrolyte. As shown in Figure 6, the cathode (positive) plate is usually made from lead dioxide (PbO_2) while porous (spongy) lead (Pb) is used for the anode (negative) plate. When the sulphur from the electrolyte is captured by the lead in both plates, the battery is discharged. The sulphur is released back to the electrolyte during the charging phase. [14, 59]

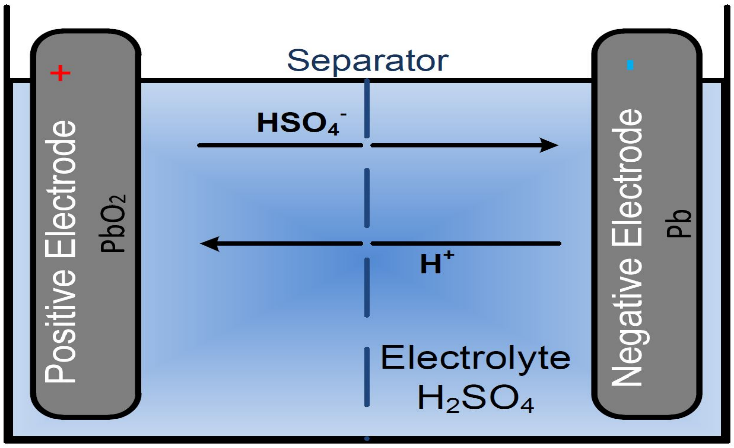


Figure 6: Structure of lead-acid battery [21]

Lead-acid batteries are commonly utilized for power quality applications and several spinning reserve applications. However, they are not usually preferred for utility scale applications because of their low energy density and small cycling life. [10] Some of the major advantages and disadvantages of lead-acid battery are:

- **Advantages:** Lead-acid battery has low capital cost and there is no complexity in the manufacturing process [34]. Production does not depend on location and there are plenty of manufacturers globally [21]. Lead-acid battery has quick response times and low self-discharge [37].
- **Disadvantages:** Due to its weak performance at low temperature, lead-acid battery needs a thermal management system. Also, low energy density and short lifetime are major barriers. [10] Lead is a heavy metal which is harmful to the environment. Therefore the usage of lead is limited by different authorities [11].

3.5 Sodium sulphur (NaS) battery

Sodium sulphur battery is composed of molten sodium as the negative plate and molten sulphur as the positive plate. They are separated by using solid beta alumina as the electrolyte. A sodium sulphur battery has high temperature requirements of (300-350)°C to perform. [11] The discharge phase is completed when Na^+ ions, which are produced from the oxidation of the sodium plate, are carried to the cathode through the electrolyte. The battery is charged with the flow of the ions in the opposite direction. [10, 14] A diagram of the process is depicted in Figure 7.

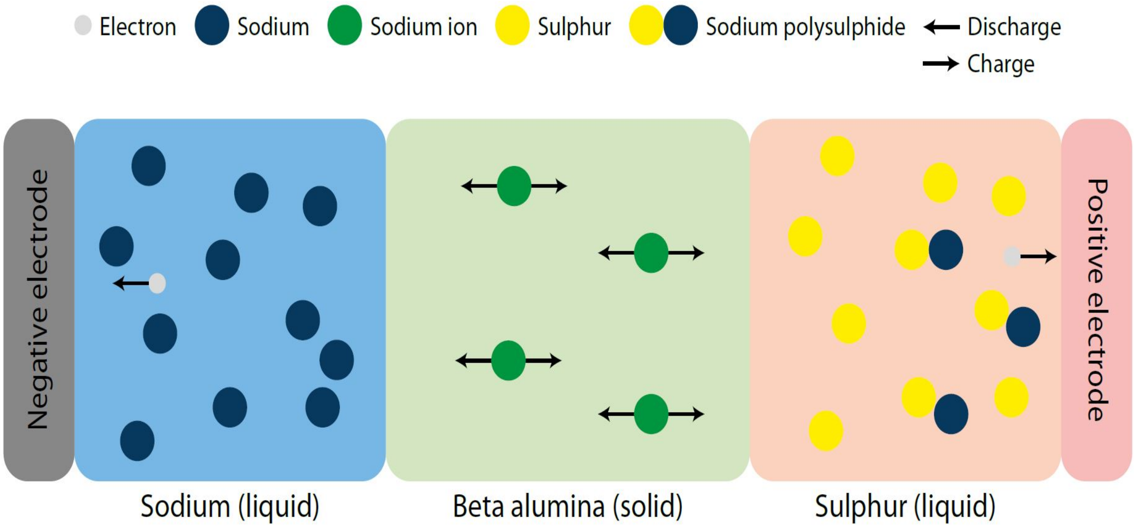


Figure 7: Structure of sodium sulphur battery [21]

Japan has extensive operational expertise on sodium sulphur batteries since this technology is substantially utilized for grid services there. The country holds more than 300 MW installed sodium sulphur battery storage power thanks to 170 nation-wide projects. [27] Some important advantages and disadvantages of sodium sulphur battery are:

- **Advantages:** The sodium sulphur battery has high round trip efficiency, high energy density, and long cycling life [34]. Moreover, the battery has almost no self-discharge and close to 100% recycling rate [14].

- **Disadvantages:** In order to maintain the required high operational temperatures, a sodium sulphur battery requires an external heater which increases operation and maintenance cost. Another option is to utilize the battery's own energy derived from its internal chemical reactions which then will reduce the battery performance. [10, 34]

3.6 Flow batteries

In contrast to traditional batteries where energy is stored in the electrodes, flow batteries reserve energy in their electrolyte solution. This makes energy capacity scalable based on the amount of electrolyte that is stored in external tanks. This difference in the working principle of flow batteries also enables affecting the power rating by only altering the active area of the cell stack. [22, 63] The working principle is linked to reduction-oxidation (redox) reactions in the electrolyte. As shown in Figure 8, when the battery is charged, the electrolyte on the left is oxidized at the anode whilst the other electrolyte on the right is reduced at the cathode. The reversed reaction occurs while discharging. [14, 37]

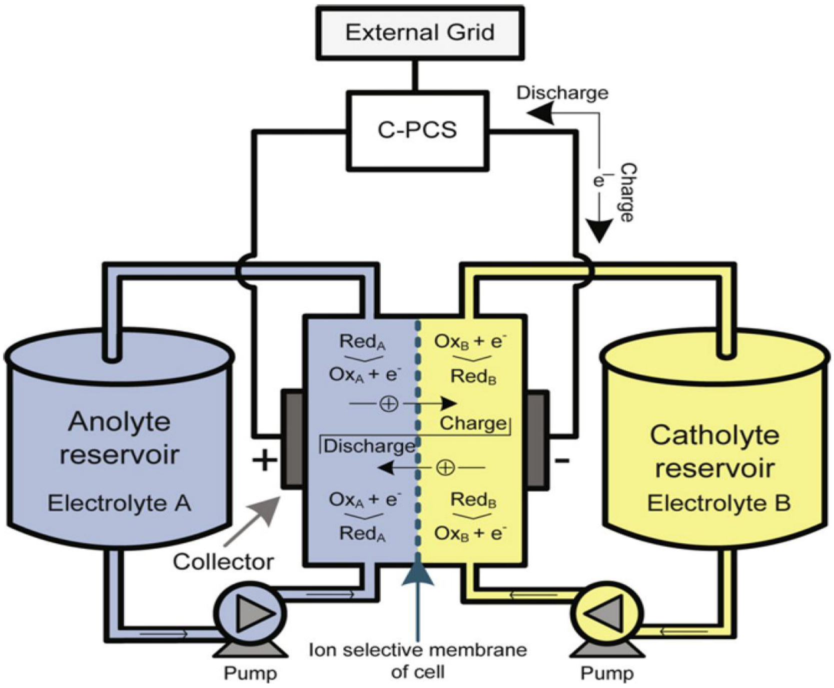


Figure 8: Structure of flow battery [14]

Some positive and negative sides of the technology are:

- **Advantages:** Flow batteries are convenient for both power and energy applications due to the concept of allowing storage in external electrolyte solutions, thereby enabling independent power and energy adjustment. [27, 63] Additionally, they can be fully discharged without causing any deterioration which enables a long lifetime and low cost of maintenance. Flow batteries also enable long storage duration based on very small self-discharge. [14]

- **Disadvantages:** Due to the risk of leakage in acidic solutions, chemical management is required in flow batteries. The complex structure of the system necessitates the use of sensors as well as pumping and flow management which potentially increases operational costs. Essential parts of the system like membrane or electrolyte tanks bring high cost. [27]

There are two types of flow batteries that will be covered in this study: the vanadium redox flow battery and the polysulfide bromide flow battery.

3.6.1 Vanadium redox flow battery (VRFB)

In a vanadium redox flow battery, energy is stored by utilizing V^{2+}/V^{3+}(oxidizing medium) redox couple at the anolyte tank, while V^{4+}/V^{5+}(reducing medium) redox couple is used at the catholyte tank in mild sulphuric acid solution [11]. During charging phase, V^{4+} ions transform into V^{5+} ions at the cathode, while V^{3+} ions are converted into V^{2+} ions at the anode. This process occurs in the reverse direction during discharging. [3] Some advantages and disadvantages of vanadium redox flow battery are:

- **Advantages:** In other flow batteries, the concept of cross-contamination creates permanent degradation of the electrolytes due to the transition of different metal ions through the membrane. This is not a concern for the vanadium redox flow battery since it features the use of vanadium in both electrolytes. [11, 22] Also, vanadium redox flow battery provides continuous, long- term, and high rate of discharge potential with rapid response times. Recovery of the electrolytes is possible at the end of life span. [27]

- **Disadvantages:** Vanadium is not available in single forms in nature. This leads to the problem of raw material treatment, and hence cost related issues arrise [22]. High corrosion tendency of V^{5+} necessitates using more costly system parts such as membranes and vessels [24].

3.6.2 Polysulfide bromide (PSB) flow battery

In a polysulfide bromide flow battery, sodium polysulfide and sodium bromide are employed as the electrolytes which are separated with a polymer membrane. Only (positive) sodium ions are allowed to pass through this separator. [10] The battery is charged when bromide ions are converted to tribromide ions at the positive plate, while reduction of dissolved sodium ions to sulphide ions takes place in the negative electrode. The opposite process applies for the discharge phase. [14] Some advantages and disadvantages of polysulfide bromide flow battery are:

- **Advantages:** A polysulfide bromide flow battery is convenient for long-duration storage due to its zero self-discharge rate [14]. In addition, Diaz-Gonzalez [14] states according to Ponce-de-Leon [13] that the chemical materials of the battery have high abundance rate as well as moderate costs. Also, a polysulfide bromide flow battery can provide quick response times [37].

- **Disadvantages:** Chemical reactions in a polysulfide bromide flow battery generate bromine and sodium sulfate which are environmentally hazardous materials. The technology itself has not yet been practically proven in large-scale storage applications. [37]

3.7 Nickel-cadmium (NiCd) battery

A nickel-cadmium battery is formed of a spongy positive electrode of nickel hydroxide $Ni(OH)_2$, negative plate of a metallic cadmium, and an alkaline electrolyte [1, 37]. The battery is charged when nickel hydroxide is converted into nickel oxyhydroxide and metallic cadmium becomes cadmium hydroxide. The process occurs in the opposite direction during discharge. [1] The structure of a nickel-cadmium battery is shown in Figure 9.

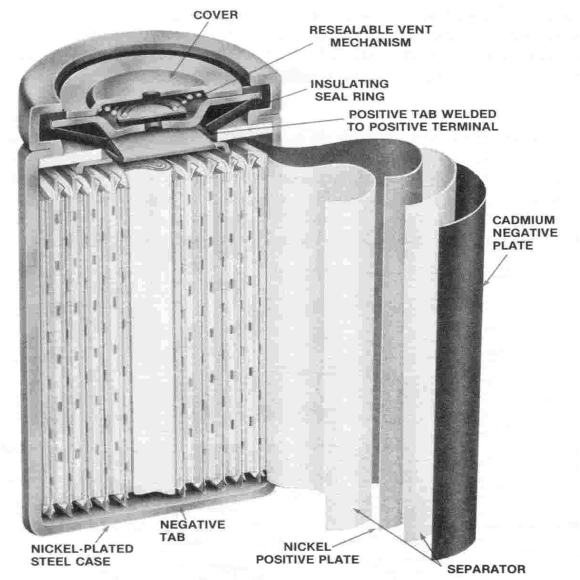


Figure 9: Structure of a nickel cadmium battery [41]

Nickel-cadmium battery is one of the most mature battery storage technologies which is widely used for portable power applications [10, 59]. However, the technology has not yet been commercially satisfactory enough for utility applications [37]. The following positive and negative aspects of the technology aid in understanding the underlying reason for this.

- **Advantages:** Nickel-cadmium batteries have high robust reliabilities and are easy to maintain [10]. They also have higher energy density and longer cycling life compared to lead-acid batteries [22]. However, depth of discharge (DOD) is an important determinant on its cycling life, for e.g. at 10% DoD, a nickel cadmium battery can last more than 50,000 cycles [14].

- **Disadvantages:** Because of high cost of manufacturing, nickel-cadmium technology requires high energy capital investment. Moreover, cadmium as a heavy metal poses a threat to the environment. [10] Finally, it also experiences a memory effect which means that the battery gets accustomed to operating in a certain cycle range due to repeated charging cycles before the battery is fully discharged [59].

3.8 Lithium-ion battery

A typical lithium-ion battery is made of a lithium metal oxide cathode, mostly graphite anode, a separator, and an electrolyte containing lithium salt dissolved in organic solvents. To increase the conductivity, the cathode is covered with an aluminum foil, while a copper foil is used for the anode. [65] As illustrated in Figure 10, during discharge phase, Li^+ ions flow through the electrolyte from anode to the cathode [59].

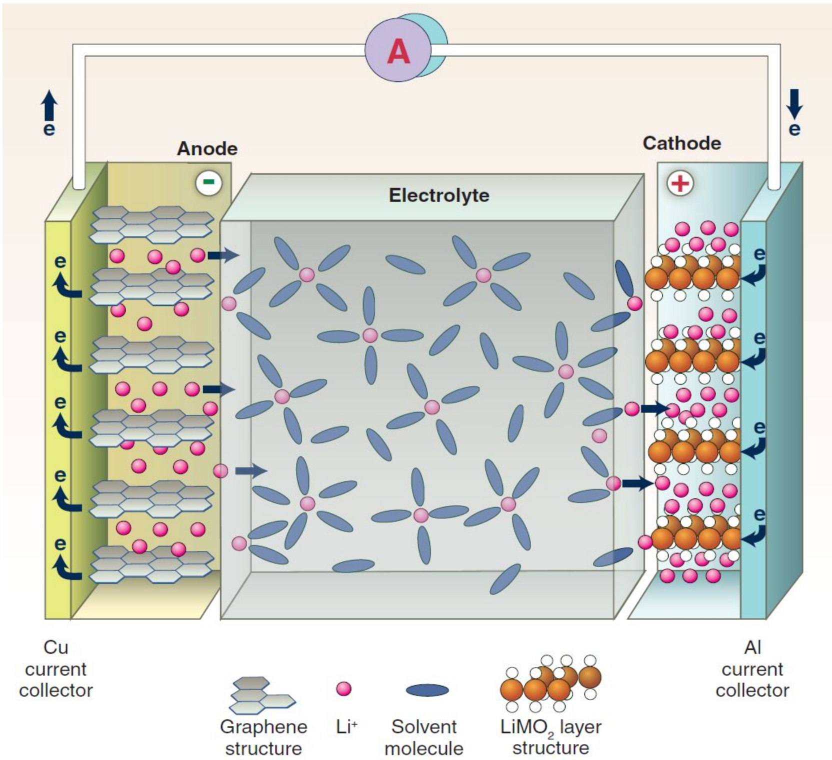


Figure 10: Structure of lithium-ion battery [15]

Some advantages and disadvantages of lithium-ion battery are:

- **Advantages:** Lithium-ion battery has high energy density and can deploy higher voltage than nickel or lead based batteries. This enables it to reach the desired pack voltage with less individual cells. It also has bigger cycle life compared to other batteries. [59] Lithium-ion battery also has quick charging and discharging capability [14] [62].

- **Disadvantages:** The life span of a lithium-ion battery is affected by cycle depth of discharge [37]. Thermal management is essential for this battery to operate properly due to its sensitivity to temperature changes [14]. In parallel with this, lithium-ion battery tends to experience thermal runaways (rapid increase of temperature in short time which might result in explosion) because of over-charging or discharging which raises safety concerns [11].

The most common batteries in the market are named according to their Li^+ ion provider in the cathode, as it controls their cell characteristics [65]. In that regard, five different types of lithium-ion batteries are considered in this study.

3.8.1 Lithium cobalt oxide (LCO)

Lithium cobalt oxide is the first commercialized chemistry which can last up to a few years. Lithium cobalt oxide is a proven technology with high maturity and high specific energy. It is commonly used for consumer electronics like mobile phones, laptops, and tablets. [65] However, this battery is not suitable for large-scale use such as electric vehicle (EV) applications due to high content of cobalt which is an expensive material [4]. Apart from this, its unsteady character at high temperatures (above 130°C) and hence high tendency to experience a thermal runaway is a major drawback [59].

3.8.2 Lithium manganese oxide (LMO)

Compared to lithium cobalt oxide, lithium manganese oxide chemistry can have longer cycling life, while its energy density is remarkably lower. The battery employs abundant and environmentally friendly elements rather than cobalt. [65] Manganese is favourable since it is notably cheaper and less harmful than cobalt or nickel [43]. Thanks to its high thermal stability, the battery can operate up to 250°C safely [6, 65].

3.8.3 Lithium iron phosphate (LFP)

Lithium iron phosphate is a naturally safer type of battery than other lithium-ion battery chemistries [4]. As a result of high availability and low cost of iron phosphate as well as having strong power capability, this battery is an optimal candidate for electric vehicles [4, 59]. However, Zubi [65] claims that lithium iron phosphate's comparably small specific energy makes its market share negligible, while making it a better fitting technology both for e-bikes and power supply systems.

3.8.4 Lithium nickel cobalt aluminium oxide (NCA)

With its low cobalt content, lithium nickel cobalt aluminium oxide has emerged as the first commercial trial aimed at replacing lithium cobalt oxide's expensive cobalt substance by utilizing the nickel element. High specific power, impressive specific energy and reasonable price are some of the positive attributes which make this chemistry a perfect match for electric vehicles. [4, 65] On the other hand, lithium nickel cobalt aluminium oxide is fragile in moist conditions [6].

3.8.5 Lithium nickel manganese cobalt oxide (NMC)

In comparison to lithium nickel cobalt aluminum oxide, lithium nickel manganese cobalt oxide battery has better cycle life, but lower specific energy. Nickel content determines the amount of specific energy, while manganese is used to adjust the specific power aspect. [65] Based on the share of the elements within the chemistry, these batteries can appear in various structures like NMC 111 which is the simplest form. More energy dense type is NMC 532/622 where cobalt content is lowered. The latest and state of the art form is NMC 811 in which the highest theoretical performance is presented [4].

3.9 Supercapacitors

Supercapacitors, also known as ultracapacitors or double-layer capacitors, are positioned in between traditional capacitors and rechargeable batteries based on their combined characteristics. For instance, the energy density of supercapacitors is higher than the energy density of conventional capacitors, but less than the energy density of batteries. [37] The structure of supercapacitors consists of an anode and a cathode which are detached by an electrolyte as well as a membrane separator preventing potential short-circuits. In this regard, the structure is similar to that of batteries. [24] Supercapacitors store energy in the electric field created between the electrodes [20]. Figure 11 shows a diagram of a typical structure of supercapacitors.

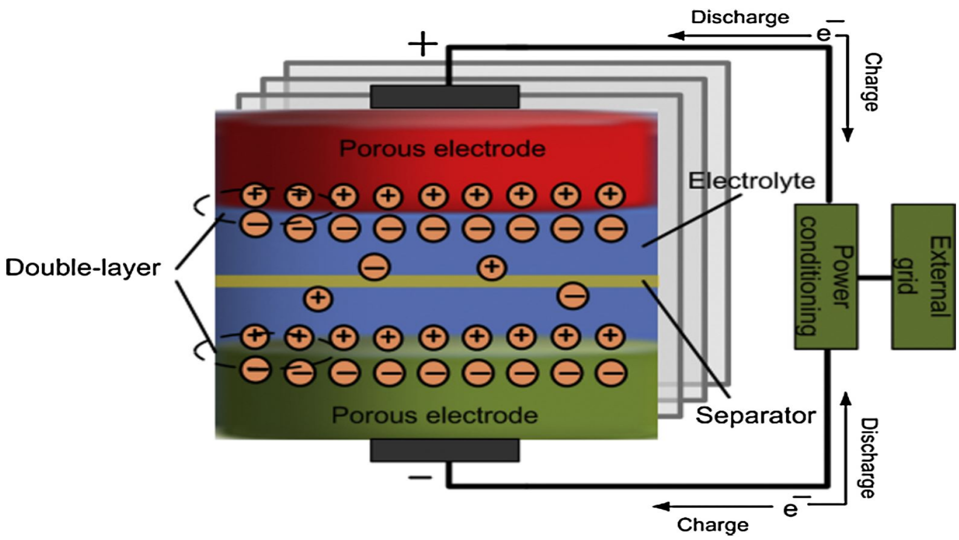


Figure 11: Structure of supercapacitor [37]

Supercapacitors are used for short-term storage applications due to their small energy density, high rate of self-discharge, and high capital costs [11]. Some positive and negative sides of supercapacitors are:

- **Advantages:** Owing to their low internal resistance, supercapacitors allow very rapid charging and discharging. They are highly durable, reliable and easy to recycle. They can also operate up to a cycle life of one million cycles under various environmental conditions with no maintenance required, apart from replacing the solvent every 5 years. [11] Moreover, they exhibit outstanding power density [11, 14].

- **Disadvantages:** Supercapacitors generally have limited storage duration differing from milliseconds to several minutes [22]. Regardless of performed cycles, the solvent tends to fail every 5 years. Moreover, supercapacitors are prone to leak energy, they have a much smaller energy density than batteries, and they are capital intensive systems. [11]

3.10 Superconducting magnetic energy storage (SMES)

As demonstrated in Figure 12, the generic concept of superconducting magnetic energy storage includes a superconducting coil part, a unit for power conditioning, and a subsystem for refrigeration and a vacuum [37]. While direct current (DC) is circulating through a superconducting coil, a magnetic area where the energy is stored is being generated. This type of a coil is not damaged by time nor the number of storage cycles. [20] It is critical to realize that the system does not operate with an ordinary coil under direct current due to potential resistance. However, a superconducting coil allows the system to perform with close to zero losses since superconducting materials create hardly any resistance. [1, 22, 37] A power converter enables the system to discharge the stored energy by delivering it to the alternating current (AC) system [37].

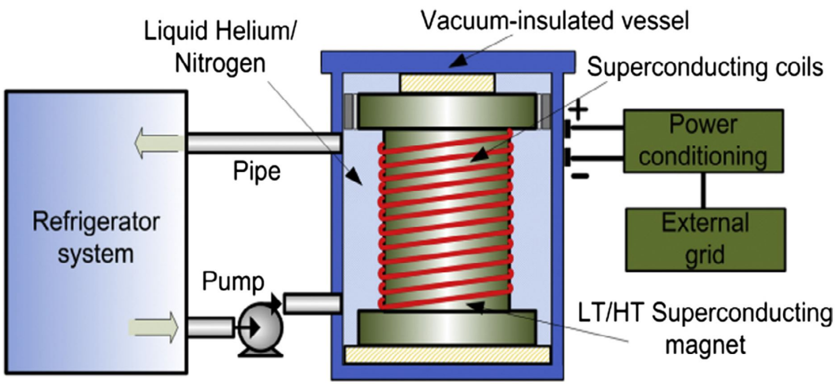


Figure 12: Structure of superconducting magnetic energy storage [37]

Some major advantages and disadvantages of superconducting magnetic energy storage are:

- **Advantages:** Very satisfactory storage efficiency (around 97%) and quick reaction time of several milliseconds are major advantages of a typical superconducting magnetic storage system, however these characteristics are valid only for short duration [10]. There is a potential for continuous energy storage under the condition that there is sufficient supply of energy for the cooling system [11]. A superconducting energy storage system can also have a lifetime of more than 20 years, and it provides very high power density [1].

- **Disadvantages:** Requiring high capital cost and creating environmental concerns due to the formation of powerful magnetic fields are important disadvantages of superconducting magnetic energy storage [20, 37, 63]. Additionally, the sensitivity of the coil to small changes in temperature and a high rate of self-discharge are also important challenges [37].

3.11 Hydrogen storage and fuel cells

Figure 13 represents a generic hydrogen storage concept which essentially includes an electrolyzer, a storage vessel, and a fuel cell unit [11]. In other words, a hydrogen storage system has three major processes: production, storage and utilization of the stored hydrogen [63]. Steam methane reforming of natural gas which stands for almost half of the world hydrogen supply is the major production method [12]. However, several studies have pointed out that steam methane reforming is creating dangerous impacts to the environment, while water electrolysis is a less harmful method of hydrogen generation [51]. In electrolysis, water is separated into hydrogen and oxygen by using a direct current source [64].

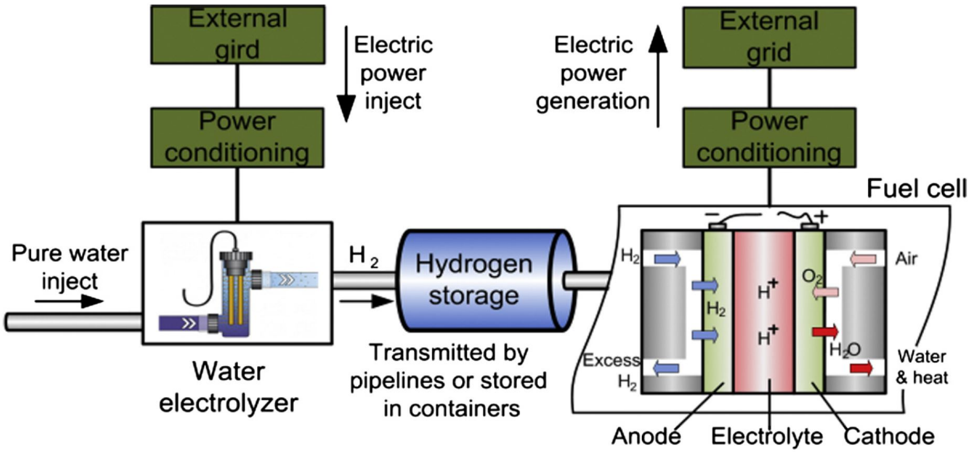


Figure 13: Structure of hydrogen storage and fuel cell [37]

Hydrogen can be stored in different forms such as compressed gaseous hydrogen, cold liquid hydrogen, hydrogen compounds stored physically or chemically within hydrides [20, 51]. Compressed hydrogen storage with high pressure is the most common option for stationary applications. The storage can be achieved both aboveground in special vessels and underground in salt caverns or pipes. [11] When it is time to convert chemical energy back to electrical energy, fuel cell is one of the most promising conversion technologies [60]. Some of major advantages and disadvantages of hydrogen storage and fuel cells are:

- **Advantages:** Hydrogen can provide as high energy density as li-ion batteries [63]. It is also possible to maintain 100% storage efficiency [22]. In addition, compared to traditional combustion engines, fuel cells are more efficient, they cause less greenhouse gas emissions, and they require less maintenance. Fuel cells can also operate in a wider range of temperatures for a longer duration than batteries, and they are capable of working with various fuel types. [60]

- **Disadvantages:** Main challenges of hydrogen storage and fuel cells are low overall efficiency and extremely large capital costs [63]. Also, safety concerns especially for pressurised gas storage of hydrogen are critical [22].

4 Comparing technical characteristics of storage technologies

This chapter is dedicated to evaluate the storage technologies from a technical point of view. In order to highlight the most crucial characteristics, Figure 18 which includes all the data that is mentioned during this section is created after a comprehensive analysis of different resources. Based on various discussions from several sources about promising technologies for the future, primary technical properties of interest have been selected as the following:

- Energy density
- Specific energy
- Self-discharge
- Storage duration
- Power rating
- Cycle efficiency (round trip efficiency)
- Discharge efficiency
- Cycle life (cycles)
- Lifetime (years)
- Maturity
- Energy capital cost
- Power capital cost
- Operation and maintenance costs

Due to their importance for storage technologies, the properties mentioned above shall be discussed in detail. Additionally, some properties which are considered to be less significant will be briefly introduced. Those include the following:

- Power density
- Specific power
- Discharge time
- Response time

4.1 Primary technical properties

Energy density

By definition, energy density refers to the energy capacity per unit volume. This means that it has a direct impact on the size of the storage system. Three technologies with the highest energy density are:

1. Hydrogen storage 2360 Wh/L (in liquid form)
2. Lithium-ion battery 200-500 Wh/L
3. Sodium sulphur battery 150-300 Wh/L

Hydrogen storage has the highest energy density with a range of 500-3000 Wh/L. However, due to its low volumetric energy density in its natural state, hydrogen must be either compressed between 200 and 700 bar or liquified in order to reach high energy density values [19]. The energy density in compressed gas form (530-750 Wh/L at 200-300 bar) is much lower than the energy density in liquid form (2360 Wh/L) [22].

For lithium-ion battery, potential increase in the energy density is linked mainly to material improvements. This would also enable significant manufacturing cost reductions due to the fact that the same battery capacity would be provided with less active materials [27].

In addition, pumped hydro storage with 0,5-1,5 Wh/L and compressed air energy storage with 2-6 Wh/L energy density, which are proven large scale storage technologies, are staying far below the mentioned levels. This also explains why they require larger areas compared to other technologies [22].

Rest of the technologies can be categorized in the mid range: nickel-cadmium battery with 60-150 Wh/L, lead-acid battery with 50-80 Wh/L, polysulfide bromide flow battery with 20-30 Wh/L, vanadium redox flow battery with 16-33 Wh/L, and supercapacitors with 10-30 Wh/L.

Specific energy

Specific energy represents the existing (stored) energy per unit weight. Thereby specific energy directly determines the weight of a storage system. Top three technologies with the greatest specific energy values are:

1. Hydrogen storage 800-10000 Wh/kg
2. Lithium-ion battery 70-250 Wh/kg
3. Sodium sulphur battery 150-240 Wh/kg

Among mechanical energy storage category, liquid air storage stands out with a remarkable value of 214 Wh/kg. It is followed by compressed air energy storage having a moderate value of 30-60 Wh/kg and pumped hydro with a really low figure of 0,5-1,5 Wh/kg.

When it comes to the other batteries, nickel-cadmium battery and lead-acid battery have moderate specific energy values of 55-75 Wh/kg and 30-50 Wh/kg, respectively. In addition, technologies that have relatively low values compared to the other ones are polysulfide bromide flow battery with 15-30 Wh/kg, vanadium redox flow battery with 10-30 Wh/kg, supercapacitors with 0,05-15 Wh/kg, and superconducting magnetic energy storage with 0,5-5,0 Wh/kg.

Self-discharge and storage duration

Self-discharge can occur in various forms such as heat losses, air leakages etc. depending on the different technologies. Moreover, it is highly related to storage duration. For example, in order to achieve seasonal (long- term) energy storage, self-discharge rate should be almost zero [22]. In other words, self-discharge rate and storage duration are inversely proportional.

In this regard, hydrogen storage, sodium sulphur battery, vanadium redox flow battery, polysulfide bromide battery, compressed air energy storage, liquid air storage, and pumped hydroelectric technology can store energy for hours to months or even longer term due to their small or almost zero self-discharge rates.

Lithium-ion battery as well as lead-acid battery with a daily self-discharge rate of 0,1-0,3%, and nickel-cadmium battery with a rate of 0,2-0,6% are suitable for short storage duration of minutes to days. Supercapacitors and superconducting magnetic energy storage are appropriate for storage applications of seconds to hours due to their extremely high daily self-discharge rates of 20-40% and 10-15%, respectively. These technologies are not suitable for seasonal storage, but rather well-suited to short-term energy shifting applications. Figure 14 shows a summary of these technologies' loss values within the expected duration frame. They are calculated, for simplification, by using direct proportion method after assuming average daily loss rates (on the left) from each technologies range in Figure 18. For example, if 30% loss occurs in 24 hours, it will take 8 hours to lose 10% for supercapacitors based on linear assumption. With the assumption of 10% loss as a safety threshold, appropriate energy shifting methods are assigned on the very right column.

Average daily loss	Loss of stored energy		5%	10%	50%	100%	Maximum feasible energy shifting
30%	Supercapacitors	hours	4	8	40	80	from day to night
15%	Superconducting magnetic storage	hours	8	16	80	160	for one day
0,4%	Nickel-cadmium battery	days	12,5	25	125	250	for one week
0,2%	Lithium-ion battery	days	25	50	250	500	for one month

Figure 14: Critical self-discharge rates and suitable energy shifting method

Power rating

Power rating is an important factor that determines the size of a storage system [24]. It is also used for finding the most suitable storage technology for particular applications due to their specific requirements of power ratings. For instance, some typical energy management applications like time shifting and peak shaving requires above 100 MW power rating for large scale management, while 1-100 MW is needed for medium/small scale. [37] Likewise, a power rating range of 1 kW-10 MW is demanded by some bridging power applications such as load following and spinning reserve [1]. Three technologies with the greatest power rating values are:

1. Pumped hydro storage 100-5000 MW
2. Fuel cells 0,1-1000+ MW
3. Compressed air energy storage Up to 300 MW

Based on the values in Figure 18 combined with the requirements of the applications mentioned above, the relevant technologies are sorted as the following:

- Large scale energy management applications: Pumped hydro storage (100-5000 MW), compressed air energy storage (up to 300 MW), fuel cells (0,1-1000+ MW), and liquid air storage (10-200 MW) are suitable technologies for large scale energy management applications.
- Medium/small scale energy management and bridging power applications: Lithium-ion battery (1-100 MW), fuel cells (0,1-1000+ MW), lead-acid battery (0-40 MW), sodium sulphur battery (up to 34 MW), and nickel cadmium battery (0-40 MW) seem to be well-suited for both types of applications. On the other hand, vanadium redox flow battery (0,03-3 MW), polysulfide bromide flow battery (1-15 MW), supercapacitors (0-0,3 MW), and superconducting magnetic energy storage (0,1-10 MW) are favorable for bridging power applications.

Cycle efficiency (round trip efficiency) and discharge efficiency

Cycle efficiency is related to charging efficiency, self-discharge, and discharging efficiency. With the simplest formulation, cycle efficiency can be calculated as the multiplication of charging efficiency, storage efficiency (which is 1 minus self-discharge), and discharging efficiency. Three technologies with the greatest cycle efficiency and discharge efficiency values are:

1. Superconducting magnetic energy storage 95-98% (cycle efficiency), 95% (discharge efficiency)
2. Supercapacitors 90-97% (cycle efficiency), 95% (discharge efficiency)
3. Lithium-ion battery 85-95% (cycle efficiency), 85% (discharge efficiency)

The technologies having cycle efficiencies above 60% like pumped hydro storage, liquid air storage, all batteries including flow batteries, supercapacitors, and superconducting magnetic energy storage are mostly at the stage of completed or early commercialization, Figure 18 [37]. On the other hand, compressed air energy storage is breaking this relation by being still a proven (commercialized) technology, but having a rather low efficiency of 42,54%. Hydrogen storage is the least efficient technology with a significantly low value of 30-50% efficiency.

Lifetime and cycle life

Lifetime refers to the shelf life of a system which is depicted in years, while cycle life presents the number of full cycles until the end of life of the storage system [27]. Three technologies with the greatest lifetime and cycle life values are:

1. Supercapacitors 50000+ cycles (cycle life), 10-30 years (lifetime)
2. Pumped hydro storage 10000-30000 cycles (cycle life), 30-60 years (lifetime)
3. Compressed air energy storage 8000-12000 cycles (cycle life), 20-40 years (lifetime)

Pumped hydro storage and compressed air energy storage together with vanadium redox flow battery are providing an average cycle life above 10000. For mechanical storage technologies, cycle life is mainly determined by the durability of mechanical components [37]. In addition, supercapacitors and superconducting magnetic energy storage are providing an extensive number of cycles, that is above 20000. On the other hand, even though the other battery technologies have reasonable cycle life, chemical deterioration with time is remarkably shortening their lifetime [37].

Maturity

The maturity of a storage system refers to the degree of commercialization, technical risk, and economic gains associated with the technology [37]. The level of operational expertise is also a vital indicator that determines the maturity stage of a technology. Additionally, the higher maturity level achieved the lower the cost of a technology becomes. [3]

Wang et al. [57] have discussed a framework called "technology readiness level (TRL)" in order to measure the maturity level of a particular technology. In Figure 15, this concept which includes ten levels is explained (TRL0 is the lowest level and TRL9 is the highest one). In addition, (with this present study) the approach is improved by combining the readiness levels with the maturity information in Figure 18. Based on that, different maturity categories are assigned to each readiness level and the technologies are grouped under each category. None of the technologies covered in this study belong to the "research and development" category. Overall, pumped hydro storage and lead-acid battery are included in the most matured technologies. On the other hand, compressed air technology is not included in this category since it still requires some progress in its round trip efficiency [3].

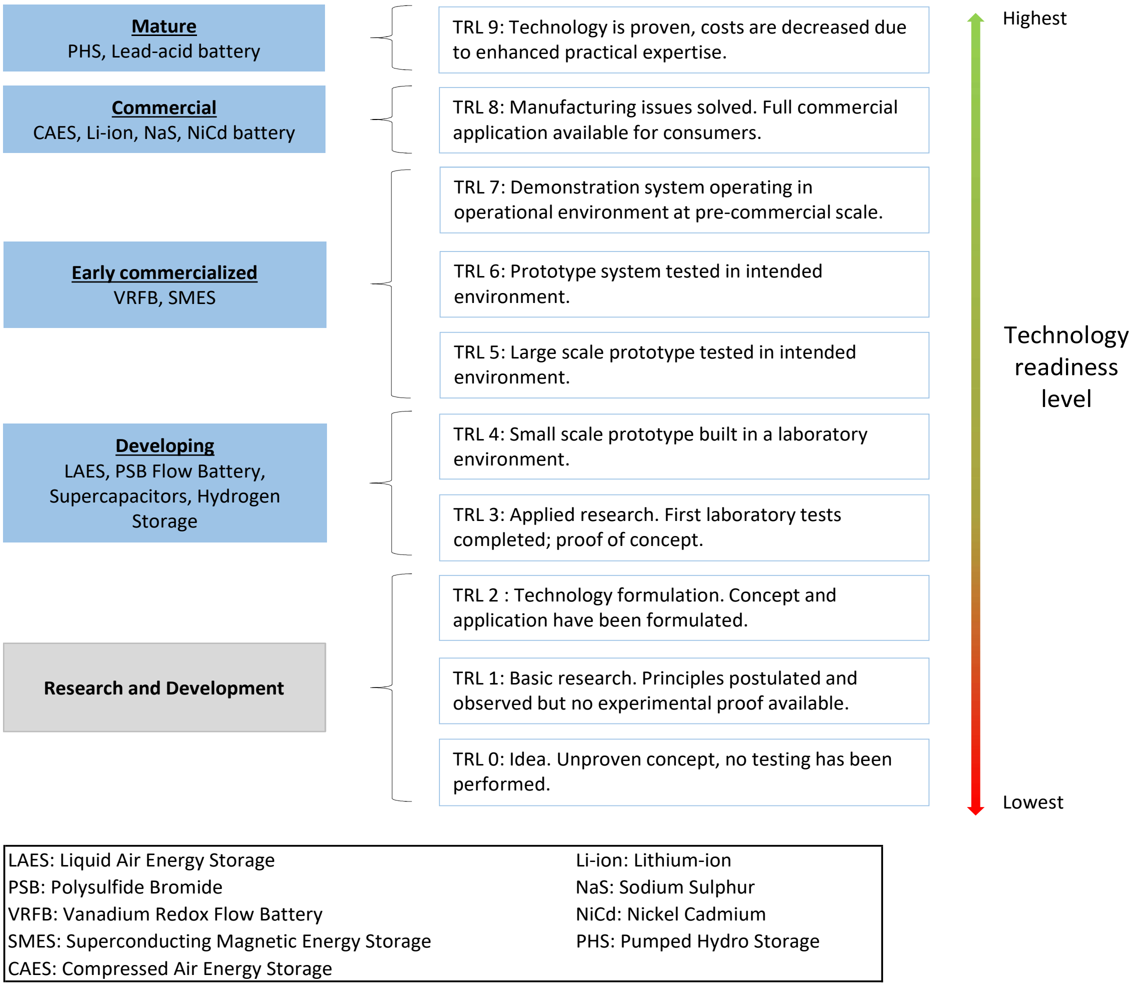


Figure 15: Maturity of storage technologies, adapted from Wang et al. [57]

Energy capital cost, power capital cost, and operation and maintenance costs

Figure 16 depicts energy capital costs and power capital costs of energy storage technologies on a single graph. It is useful to see them at the same time for a better comparison.

Some technologies like supercapacitors (100-400 USD/kW) and superconducting magnetic storage (200-489 USD/kW) are more suitable for power driven applications due to their lower capital cost per unit of power than energy capital cost [1, 3]. There are several factors affecting capital costs such as the location of system, the size of unit, and the duration of construction or installation [37]. In terms of the cost per unit of energy, pumped hydro storage (10-20 USD/kWh), compressed air energy storage (2-120 USD/kWh), and hydrogen storage (1-10 USD/kWh) are the cheapest technologies.

When it comes to operation and maintenance cost, it is critical to consider this parameter for the sake of a better economic lifetime analysis of any technology. For example, relatively high operation and maintenance cost of lead-acid battery (50 USD/kW/year) makes it inadequate for large-scale storage applications even though its cost per unit of energy is relatively low (100-400 USD/kWh). [37] In addition, sodium sulphur battery and vanadium redox flow battery have high operation and maintenance costs with the values of 80 USD/kW/year and 70 USD/kW/year, respectively. Values for all storage technologies were not found from the resources covered within this study.

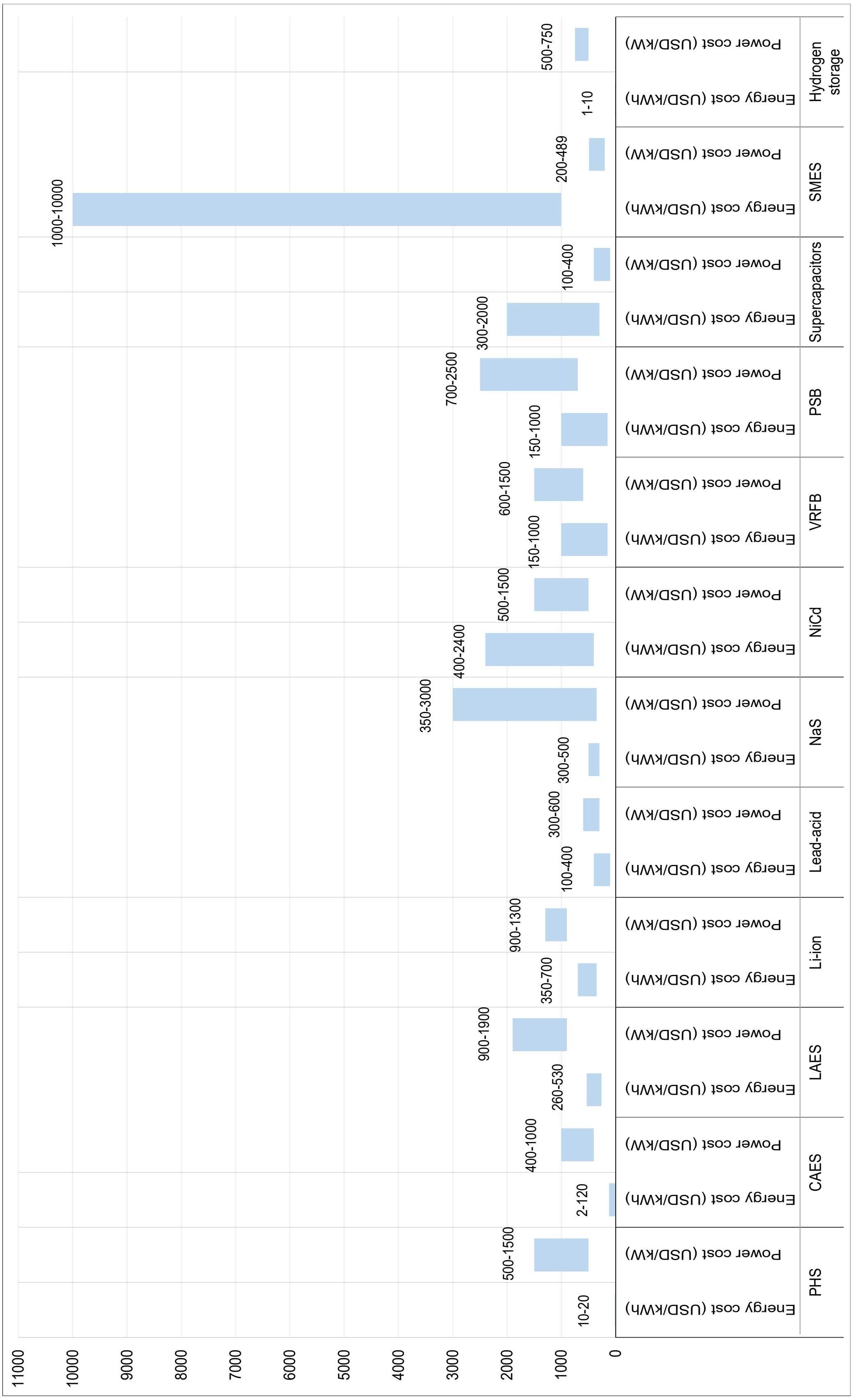


Figure 16: Energy and power capital cost of energy storage technologies, data from Figure 18

4.2 Secondary technical properties

The values for power density, specific power, discharge time, and response time are presented in Figure 18 as well.

In terms of power density, supercapacitor is the most suitable technology for high-power applications with its outstanding value of 100000 W/L [1]. Among battery technologies, lithium-ion battery presents the highest range of power density with 1300-10000 W/L. This characteristic, together with its high energy density, has increased its use in portable devices and made it suitable for storage and transportation applications [37]. In that sense, hydrogen storage is falling behind these technologies with a relatively low power density of above 500 W/L. Mechanical storage technologies have very low power density. For instance, the power density of pumped hydro storage and compressed air energy storage are 0,5-1,5 W/L and 0,5-2 W/L, respectively.

When it comes to specific power, supercapacitor and superconducting magnetic energy storage are providing the highest values, 500-5000 W/kg and 500-2000 W/kg, respectively, despite their extremely low specific energy. After these technologies, lithium ion battery is providing the best value with specific power range of 150-2000 W/kg. In addition, fuel cells can provide specific power of 500 W/kg. For batteries and supercapacitors, specific power is determined by battery chemistry and materials used, while the kinetic properties of cell parts govern this feature in the case of flow batteries and fuel cells [24].

Figure 17 helps for identifying the expected discharge duration for some important application types. Superconducting magnetic energy storage is suitable for power quality applications, while the rest of the technologies can be employed more or less for all three types of applications. The energy-to-power ratio is calculated as less than 1 (system capacity of less than 1 kWh with a power of 1kW) for discharge duration of seconds to minutes, between 1 and 10 for discharge time of minutes to hours, and greater than 10 for discharge period of days to months [11].

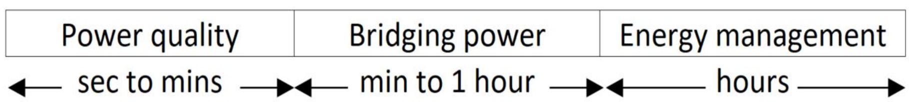


Figure 17: Applications based on discharge time [1]

Response time is an important factor that varies depending on application areas. For instance, response time of milliseconds is needed for most of power quality maintenance applications like rapid voltage decrease or flicker mitigations. Response time is also a key parameter for balancing electricity supply. In that sense, fuel cells, pumped hydro storage, batteries, compressed air energy storage, and liquid air storage can be employed for seasonal variations, while supercapacitors and superconducting magnetic energy storage can be utilized for transitory variations. [3]

Technology group		Mechanical Energy Storage			Electrochemical Energy Storage						Electric and Magnetic Energy Storage		Chemical Energy Storage
Energy Storage Technology		Pumped Hydro Storage	Compressed Air Energy Storage	Liquid Air Energy Storage	Lithium-ion Battery	Lead–acid Battery	Sodium Sulphur Battery	Nickel Cadmium Battery	Vanadium Redox Flow Battery	Polysulfide Bromide Flow Battery	Supercapacitors	Superconducting Magnetic Energy Storage	Hydrogen Storage and Fuel Cell
Abbreviations		PHS	CAES	LAES	Li-ion	LAB	NaS	NiCd	VRFB	PSB		SMES	
Energy storage													
Energy density	Wh/L	0,5–1,5 [10]	2-6 [37]	50 [22]	200-500 [3]	50-80 [10]	150-300 [37]	60-150 [10]	16-33 [10]	20-30 [37]	10-30 [1]	0,2-2,5 [22]	500-3000 [22]
Specific energy	Wh/kg	0,5–1,5 [2]	30-60 [37]	214 [37]	70-250 [22]	30-50 [10]	150-240 [3]	55-75 [63]	10-30 [3]	15-30 [37]	0,05-15 [37]	0,5-5 [63]	800-10000 [3]
Self-discharge	%	0,005-0,02 [22]	small [10]	small [37]	0,1-0,3 [22]	0,1-0,3 [63]	almost zero [37]	0,2-0,6 [63]	very low [37]	almost zero [37]	20-40 [63]	10-15 [14]	very small [22]
Storage duration		hours-months [63]	hours-months [3]	long term [37]	minutes-days [10]	minutes-days [63]	long term [37]	minutes-days [22]	hours-months [3]	hours-months [63]	seconds-hours [22]	minutes-hours [63]	hours-months [63]
Energy capital cost	USD/kWh	10-20 [2]	2-120 [2]	260-530 [22]	350-700 [2]	100-400 [37]	300-500 [3]	400-2400 [37]	150-1000 [3]	150-1000 [10]	300-2000 [10]	1000-10000 [10]	1-10 [22]
Energy charging/discharging													
Power density	W/L	0,5–1,5 [10]	0,5-2 [10]	-	1300-10000 [11]	10-700 [22]	140-180 [37]	80-600 [37]	0,5-2 [22]	up to 2 [37]	100000 [22]	1000-4000 [22]	500+ [3]
Specific power	W/kg	-	-	-	150-2000 [22]	75-415 [22]	90-230 [37]	150-300 [10]	166 [22]	-	500-5000 [22]	500-2000 [63]	500 [63]
Power rating	MW	100–5000 [10]	up to 300 [37]	10-200 [37]	1-100 [37]	0-40 [37]	up to 34 [14]	0-40 [10]	0,03-3 [10]	1-15 [10]	0-0,3 [3]	0,1-10 [63]	0.1-1000+ [22]
Discharge efficiency	%	87 [37]	70-79 [37]	-	85 [37]	85 [37]	85 [37]	85 [37]	75-82 [37]	-	95 [37]	95 [37]	59 [37]
Cycle/round trip efficiency	%	65-85 [22]	42.54 [37]	55-80 [37]	85-95 [22]	63-90 [37]	75-90 [1]	60-83 [37]	65-75 [14]	60-75 [60-75]	90-97 [37]	95-98 [37]	30-50 [22]
Discharge time		1-24 hours [63]	1-24 hours [63]	several hours [37]	minutes-hours [3]	seconds-hours [63]	seconds-hours [10]	seconds-hours [22]	seconds-10 hours [10]	seconds-10 hours [10]	milliseconds-1 hour [10]	milliseconds-minutes [22]	seconds-24+ hours [10]
Power capital cost	USD/kW	500-1500 [2]	400-1000 [37]	900-1900 [37]	900-1300 [37]	300-600 [10]	350-3000 [37]	500-1500 [10]	600-1500 [1]	700-2500 [10]	100-400 [22]	200-489 [37]	500-750 [36]
O&M costs													
O&M costs	USD/kWh	0.004 [37]	0.003 [37]	-	-	-	-	-	-	-	0.005 [37]	0.001 [37]	0,0019-0,0153 [37]
O&M costs	USD/kW/year	3 [37]	20 [37]	-	-	50 [37]	80 [37]	20 [37]	70 [37]	-	6 [37]	18.5 [37]	-
O&M costs	% of investment	-	-	-	2.5%	-	-	-	-	-	-	-	-
Lifetime													
Cycle life	cycles	10000-30000 [37]	8000-12000 [37]	-	2000-5000+ (at 80% DOD) [22]	400-1500 [22]	2500-4500 [11]	2000-2500 [63]	12000+ [3]	2000-2500 [63]	50000+ [37]	20000+ [37]	1000+ [10]
Lifetime	years	30-60 [22]	20-40 [63]	20-40 [22]	5-15 [10]	5-15 [63]	10-15 [11]	10-20 [63]	5-20 [27]	10-15 [63]	10-30 [10]	20+ [3]	20-30 [22]
Other													
Response time		minutes [11]	minutes [11]	minutes [37]	milliseconds [22]	milliseconds [22]	milliseconds [22]	milliseconds [37]	milliseconds [10]	milliseconds [22]	milliseconds [22]	milliseconds [22]	seconds-minutes [22]
Maturity		mature [3]	commercial [22]	developing [37]	commercial [22]	mature [37]	commercial [3]	commercial [22]	early commercialized [37]	developing [37]	developing [37]	early commercialized [37]	developing [3]

Figure 18: Technical characteristics of storage technologies [1–3, 10, 11, 14, 22, 27, 36, 37, 63]

5 Levelized cost of storage (LCOS) model overview

Belderbos et al. [5] define levelized cost of storage (LCOS) "*as the fictitious average electricity price during discharging needed over the lifetime of the storage plant to break even the full costs for the investor (including payments for capital).*". Levelized cost of storage is an effective concept that helps comparing various technologies by using multiple data sets. This study provides a new model to calculate levelized cost of storage for 12 different technologies up until 2050. The calculations are presented in 3 separate parts for lithium-ion battery, hydrogen storage, and other technologies. Before starting to explain each part in details, general assumptions that have been used for every technology is represented below:

- The calculations are designed for a 4-hour storage system (charging and discharging in 4 hours)(C-rate is 0.25).
- Surplus energy from renewable sources (wind and solar energy) is assumed to be used for charging the storage systems, therefore the cost of electricity supply is not incorporated into the calculations (0 USD/MWh).
- For the cost data that has been accessed in the currency of euros, a conversion rate of 1/1 is used to convert it into USDs. This assumption is used for simplifications of the calculations.
- Weighted average cost of capital (WACC) is assumed to be 8% (per year) for all storage technologies based on the educated assumptions made by experts on the topic [29]. Lifetime values for all technologies are taken as the upper limit of the ranges mentioned in Figure 18.
- All the storage systems are assumed to be experiencing 1 daily charging/discharging cycle which makes a total of 365 charging times in a year.
- Daily self discharge rates are assumed to be 0%. For all technologies, except for hydrogen storage, charging and discharging efficiencies are assumed to be equal to each other which are basically the square root of round trip efficiency.
- Balance of plant (BOP) factor, which is used for including the impact of project engineering and grid connection costs [63], is assumed to be 1.2 (20 % increase in capital expenditures (capex)), except for lithium-ion battery and hydrogen storage (balance of plant factor is taken as 1.0 which means that it is not included in the calculations).
- For the calculation steps in tables, the following equations are used:

$$\textit{Annuity factor} = \frac{WACC}{1 - \left(\frac{1}{1+WACC}\right)^{\left(\frac{1}{lifetime}\right)}} \tag{1}$$

$$\textit{C-rate} = \frac{\mathit{1}}{\textit{Charging time}\ \left(\textit{hours}\right)} \tag{2}$$

$$\textit{Storage capacity} = \textit{Required charging and discharging power} \times \textit{Charging time}\ \left(\textit{hours}\right) \tag{3}$$

$$\begin{aligned}\textit{Annual discharging capacity} = \textit{Storage capacity} \times \textit{Annual charging times}\\ \times \sqrt{\textit{Round trip efficiency}}\end{aligned} \tag{4}$$

$$\begin{aligned}\textit{Capex (USD)} = \textit{Required charging and discharging power or Storage capacity}\\ \times \textit{BOP} \times \textit{Capex (USD/kW) or Capex (USD/kWh)}\end{aligned} \tag{5}$$

$$\textit{Annual Capex} = \textit{Capex} \times \textit{Annuity factor} \tag{6}$$

$$\begin{aligned}\textit{Annual FOM costs} = \textit{Fixed O\&M (USD/kW/year) or (USD/kWh/year)}\\ \times \textit{Required charging and discharging power or Storage capacity}\end{aligned} \tag{7}$$

$$\begin{aligned}\textit{Total costs} = \textit{Annual Capex for charging and discharging}\\ + \textit{Annual FOM costs for charging and discharging}\\ + \textit{Annual Capex for storage} + \textit{Annual FOM costs for storage}\end{aligned} \tag{8}$$

$$\textit{LCOS} = \frac{\textit{Total costs}}{\textit{Annual discharging capacity}} \tag{9}$$

WACC: Weighted average cost of capital
Capex: Capital expenditures
BOP: Balance of plant
FOM: Fixed operation and maintenance
O&M: Operation and maintenance
LCOS: Levelized cost of storage

There are some other technology specific assumptions which will be mentioned while commenting on each technology's cost of storage. Moreover, the main data gathered for calculating the levelized cost of storage consists of the capital costs of power and energy as well as the round trip efficiency for each technology.

5.1 Lithium-ion battery

As a first step, the cost data (expectations) for lithium-ion battery is gathered. Figure 19 represents the capital cost data up to 2030 for a utility scale application. Since there is not any forecast after 2030, this study has assumed 3 different cost trend scenarios up to 2050. The scenarios are designed for a cost decrease of 10% (low decrease scenario), 25% (medium decrease scenario), and 50% (high decrease scenario) for every 5 years. After that, round trip efficiency value is assumed as 85% up to 2030 based on the data in Figure 18. After 2030, it is taken as 95% based on the expectation in the article of Julch [29].

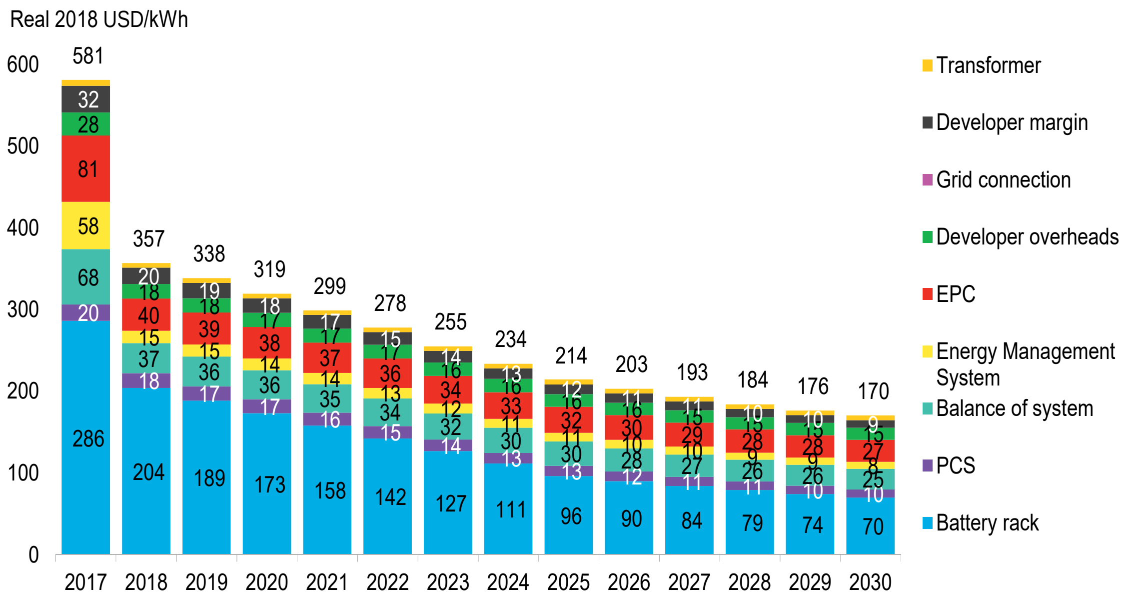


Figure 19: Expected annual lithium-ion battery capital costs (C-rate 0.25) (EPC: Engineering, procurement, and cosntruction, PCS: Power conversion system) [7]

Based on all these assumptions, levelized cost of storage is calculated by using Equations (1) to (9). Figure 21 shows the detailed steps of calculations for 10% cost decrease scenario. The rest of the scenarios have the exact same steps, except the difference of lowering the cost with different percentages after 2030. Moreover, in Figure 21, there is not any separate cost data mentioned for charging and discharging and balance of plant (BOP) factor is taken as 1.0, becauase the cost data in Figure 19 already includes all the related costs such as engineering, procurement, and construction (EPC) and power conversion system (PCS) costs. Yearly fixed cost is assumed to be 2.5% and taken as constant. Figure 20 summarizes the results for the 3 scenarios.

Cost reductions are expected due to mass production in the future for lithium-ion battery. In addition, due to rapid growth in learning curves of lithium-ion battery technology, an efficiency increase can be expected. However, none of the forecasts anticipates a possible impact of resource scarcity for important materials of lithium-

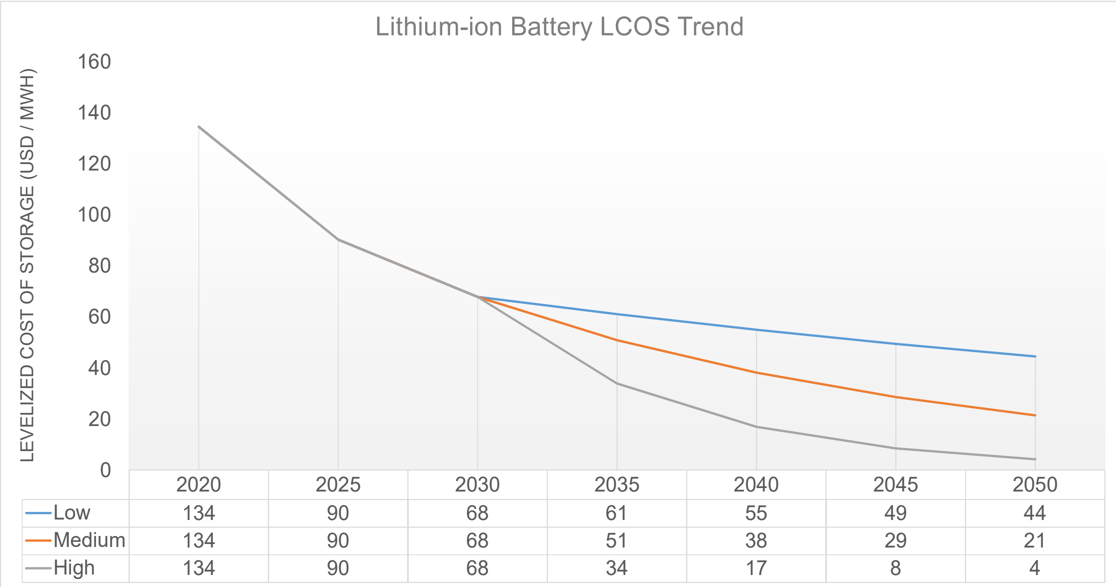


Figure 20: Levelized cost of storage (LCOS) for 3 different cost decrease scenarios - Lithium-ion battery

ion battery. This subject is elaborated in the subsequent chapter of this study. The material availability problem, with no doubt, will affect the cost of storage negatively. In this case, expecting a drastic fall in the cost can be a bit unrealistic.

Year		2020	2025	2030	2035	2040	2045	2050
Charging								
Charging time	hours	4	4	4	4	4	4	4
C-rate		0.25	0.25	0.25	0.25	0.25	0.25	0.25
Charging time	days	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Required charging and discharging power	kW	250	250	250	250	250	250	250
Storage capacity	MWh	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Annual charging times	#/year	365	365	365	365	365	365	365
Round trip efficiency	%	85%	85%	95%	95%	95%	95%	95%
Annual discharging capacity	MWh/year	337	337	356	356	356	356	356
Investment parameters								
Lifetime	years	15	15	15	15	15	15	15
Weighted average cost of capital	%	8%	8%	8%	8%	8%	8%	8%
Annuity factor		0.117	0.117	0.117	0.117	0.117	0.117	0.117
Balance of plant (BOP) factor		1.0	1.0	1.0	1.0	1.0	1.0	1.0
Charging and discharging								
Capex	USD/kW							
Capex	USD							
Annual capex	USD/year							
Fixed O&M (Operation and Maintenance)	USD/kW/year							
Annual FOM (Fixed O&M) costs	USD/year							
Storage								
Capex	USD/kWh	319	214	170	153	138	124	112
Capex	USD	319,000	214,000	170,000	153,000	137,700	123,930	111,537
Annual capex	USD/year	37,269	25,002	19,861	17,875	16,087	14,479	13,031
Fixed O&M	% of investment/year	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
Fixed O&M	USD/kWh/year	8	5	4	4	3	3	3
Annual FOM costs	USD/year	7,975	5,350	4,250	3,825	3,443	3,098	2,788
Total costs	USD/year	45,244	30,352	24,111	21,700	19,530	17,577	15,819
Levelized cost of storage (LCOS)	**USD/MWh**	**134**	**90**	**68**	**61**	**55**	**49**	**44**

Figure 21: Levelized cost of storage (low decrease scenario) - Lithium-ion battery

5.2 Hydrogen storage

Hydrogen storage is separated from the other technologies by its different levelized cost structure. The levelized cost of hydrogen storage includes 3 sets of calculations: levelized cost of production (LCOP) (water electrolysis), compression (charging) and (underground) storage cost, and discharging (fuel cell) cost. In other words, hydrogen storage cost should be tackled from the point that hydrogen is obtained till the point that it is converted into electricity. In Figure 23, the detailed steps of calculations for 3 parts and the overall levelized cost of hydrogen storage is shown. The assumptions, the formulas, and the information regarding the data collection are:

- In the levelized cost of production (LCOP) (water electrolysis) calculations, proton exchange membrane (PEM) is chosen as the method for electrolysis. Because, even though alkaline electrolysis is a quite mature technology, it is expected that the cost of proton exchange membrane electrolysis will be drastically decreasing (even to the level below the cost of alkaline electrolysis) and the technology will be commercially emerging very quickly [28, 40]. Regarding the capital expenditures (capex) data, it is assumed to be 1200 USD/kW for 2020 based on the value for 2017 in International Renewable Energy Agency's report [28]. The costs for 2025 and 2050 are taken from the study of Michalski et al.[40], while the cost for 2030 comes from the report of International Energy Agency [31]. Finally, the costs from 2030 to 2050 are extrapolated with a constant growth rate. Fixed operation and maintenance cost rate is assumed as 5 % of the capital investment [31]. Electricity price is considered as 0 USD/year since the electrolysis is assumed to be powered by a renewable energy source. Efficiency values are taken from the report of International Renewable Energy Agency [28] for 2020 (same value with 2017 in the report) and 2025, and from the report of International Energy Agency [31] for 2030 and 2050. From 2030 to 2050, the efficiency values are assumed to be growing with 1% (percen point). Annual running hours and required charging power are assumed as 1000 h/year and 250 kW, respectively. The lifetime of the electrolysis is taken as 30 years [40] and weighted average cost of capital is assumed to be 8%. After that, annuity factor is calculated by using Equation 1. The rest of the equations, Equations (10) to (14), used for production calculations are as the following:

$$Annual\ production = \frac{Required\ charging\ power \times Annual\ running\ hours}{1000} \tag{10}$$

$$Electrical\ consumption = \frac{Required\ charging\ power}{Efficiency} \tag{11}$$

$$Annual\ Fixed\ O\&M = Fixed\ O\&M \times Required\ charging\ power \tag{12}$$

$$Annual\ Capex = Capex \times Required\ charging\ power \times Annuity\ factor \tag{13}$$

$$LCOP = \frac{Total\ costs}{Annual\ production} \tag{14}$$

O&M: Operation and maintenance
Capex: Capital expenditures
LCOP: Levelized cost of production

- In the second part of the calculations, compression (charging) and (underground) storage cost, the system is assumed to be charging and discharging in 4 hours with a required charging power of 250 kW and a storage capacity of 1 MWh hydrogen. It is also assumed to be charged 365 times in a year. As the storage method, underground storage (salt caverns) is selected since it is much cheaper than the above ground one, which is 0.2-11.6 USD/kWh compared to 128-132 USD/kWh [63]. Before deciding the efficiency of the compressor, the suitable compressor type is identified. In order to store hydrogen in large scale, it is convenient to compress it to around 20 MPa in salt caverns [47]. Based on this information, from the report of International Energy Agency [31], the efficiency is chosen to be 90% for all years which is a realistic value within the range of a 18 MPa compressor, and the lifetime for the compressor is taken as 20 years from the same report. With these values, annual charging capacity is calculated as the multiplication of storage capacity, annual charging times, and compressor efficiency. Also, capital investment is 70 USD/kW for a 18 MPa compressor [31]. That is why, in our model for the 20 MPa compressor, it is assumed to be 100 USD/kW. Fixed operation and maintenance cost of the compressor is taken as 4% of the investment [40]. Additionally, for the storage section, the capital cost is taken as 280 USD/MWh and the lifetime as 30 years [40]. Annuity factors for both the compressor and the storage are calculated by using Equation 1. Annual fixed operation and maintenance cost and annual capital expenditures (capex) for the compressor are calculated by using Equation 12 and Equation 13. Equation 6 is used for calcualting annual capital expenditures of the storage section. Finally, the levelized cost of compression and storage is calculated by dividing the total cost into the annual charging capacity.

- In the last part of the calculations, discharging (fuel cell) cost, proton exchange membrane fuel cell is selected as the technology for the utilization of hydrogen. Capital expenditure values are gathered as 3200 USD/kW for 2015, 830 USD/kW for 2030, and 660 USD/kW for 2050 [31]. The data for the rest of the years in between these known cost values is calculated by extrapolating with a constant growth rate. The same method is applied for the unknown efficiency values in different years. The efficiency for 2015 (43%) is assumed to apply also in 2020, while the values for 2030 and 2050 are assumed to be 54% and 57%, respectively. Fixed cost is taken as 5% of the capital investment. [31] Annual running hours data is kept the same as it was in the production part, and fuel power is taken as the same with the required charging power of previous calculations. Electrical power is obtained by multiplying fuel power with the efficiency. The sum of levelized cost of production, compression and storage is used as the average fuel price in discharging calculations. For the annuity factor, Equation 1 is used and the lifetime of the fuel cell is calculated to be 60 years based on 60000 hours lifetime data [31] and 1000 hours of running time. Finally, the overall levelized cost of hydrogen is computed by summing up all the cost components (the last 3 rows) for each year. The remaining steps are continued based on the below formulas:

$$Fuel\ costs\ (USD/year) = Average\ fuel\ price \times Annual\ consumption \tag{15}$$

$$Fuel\ costs\ (USD/MWh\ el) = \frac{Fuel\ costs\ (USD/year)}{Annual\ production} \tag{16}$$

$$Levelized\ fixed\ O\&M\ costs = \frac{Fixed\ O\&M \times Electrical\ power}{Annual\ production} \tag{17}$$

$$Levelized\ capital\ costs = \frac{Capex \times Annuity\ factor \times Electrical\ power}{Annual\ production} \tag{18}$$

O&M: Operation and maintenance
Capex: Capital expenditures.

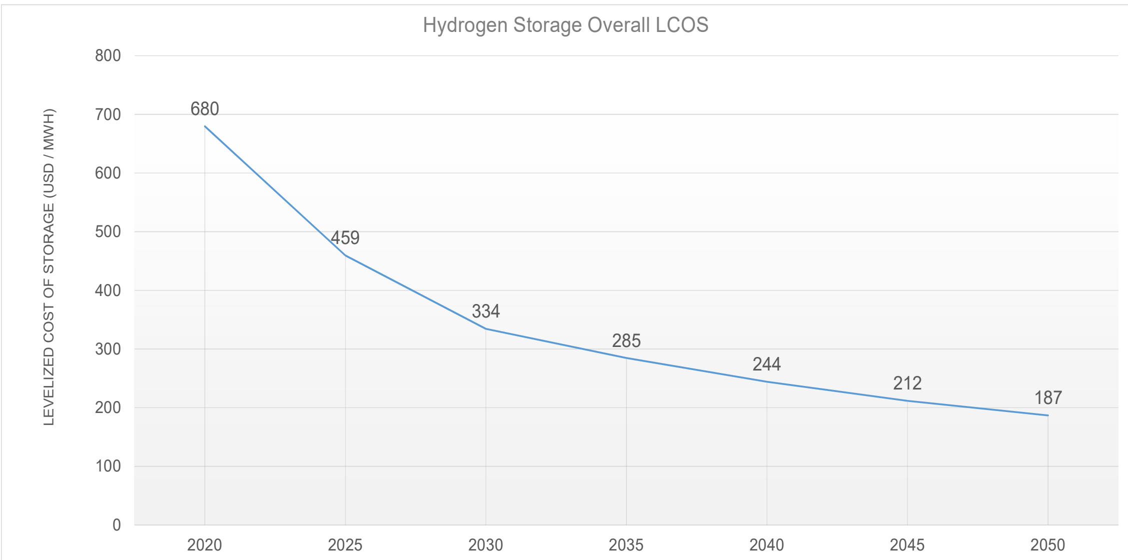


Figure 22: Hydrogen storage overall levelized cost of storage (LCOS) from 2020 to 2050

In the last part of Figure 23, it is important to realize that fuel costs are constituting more than half of the overall levelized cost of hydrogen storage. The end results for the cost values are summarized as a graph in Figure 22. Accordingly, the biggest fall is expected from 2020 to 2025 by around 30%, while the decrease rate will be lowering in the following years.

Investment parameters	Electrolysis and storage	Compressor	Fuel cell
Lifetime (years)	30	20	60
Weighted average cost of capital (%)	8%	8%	8%
Annuity factor	0.089	0.102	0.081

Year		**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydrogen Production		**Water Electrolysis (Proton Exchange Membrane)**						
Capex	USD/kW	1200	932	800	643	517	416	334
Fixed O&M (Operation and Maintenance)	USD/kW/year	60	47	40	32	26	21	17
Efficiency	%	57%	64%	82%	83%	84%	85%	86%
Annual running hours	h/year	1,000	1000	1000	1000	1000	1000	1000
Required charging power	kW	250	250	250	250	250	250	250
Annual production	MWh/year	250	250	250	250	250	250	250
Electricity consumption								
Electrical consumption	kW	439	391	305	301	298	294	291
Annual consumption	MWh/year	439	391	305	301	298	294	291
Electricity price	USD/MWh	0	0	0	0	0	0	0
Total costs								
Electricity costs	USD/year	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Annual Fixed O&M (Operation and Maintenance)	USD/year	15,000	11,650	10,000	8,038	6,461	5,194	4,175
Annual capex	USD/year	26,648	20,697	17,765	14,280	11,479	9,227	7,417
Total costs	USD/MWh	41,648	32,347	27,765	22,319	17,940	14,421	11,592
Levelized cost of production (LCOP)	**USD/MWh**	**167**	**129**	**111**	**89**	**72**	**58**	**46**

Year		**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Charging		**Compressor**						
Charging time	hours	4	4	4	4	4	4	4
C-rate		0.25	0.25	0.25	0.25	0.25	0.25	0.25
Charging time	days	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Required charging power	kW	250	250	250	250	250	250	250
Storage capacity	MWh	1	1	1	1	1	1	1
Annual charging times	#/year	365	365	365	365	365	365	365
Compressor efficiency	%	90%	90%	90%	90%	90%	90%	90%
Annual charging capacity	MWh/year	329	329	329	329	329	329	329
Capex (compressor)	USD/kW	100	100	100	100	100	100	100
Fixed O&M (Operation and Maintenance)	USD/kW/year	4	4	4	4	4	4	4
Capex (compressor)	USD	25,000	25,000	25,000	25,000	25,000	25,000	25,000
Annual capex (compressor)	USD/year	2,546	2,546	2,546	2,546	2,546	2,546	2,546
Annual Fixed O&M (Operation and Maintenance)	USD/year	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Total	USD/year	3,546	3,546	3,546	3,546	3,546	3,546	3,546
Storage		**Underground (Salt Caverns)**						
Capex (storage)	USD/MWh	280	280	280	280	280	280	280
Capex (storage)	USD	280	280	280	280	280	280	280
Annual capex (storage)	USD/year	25	25	25	25	25	25	25
Total costs		3,571	3,571	3,571	3,571	3,571	3,571	3,571
Levelized cost of compression and storage	**USD/MWh**	**11**	**11**	**11**	**11**	**11**	**11**	**11**

Year		2020	2025	2030	2035	2040	2045	2050
Discharging		**Fuel Cell (Proton Exchange Membrane Fuel Cell)**						
Capex	USD/kW	2041	1301	830	784	740	699	660
Fixed O&M (Operation and Maintenance)	USD/kW/year	102	65	42	39	37	35	33
Efficiency	%	43	49	54	55	56	57	57
Production								
Annual running hours	hours/year	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Fuel power	kW	250	250	250	250	250	250	250
Electrical power	kW	107.5	121.25	135	137.5	140	142.5	142.5
Annual consumption / production								
Annual consumption	MWh/year	250	250	250	250	250	250	250
Annual production	MWh/year	107.5	121.25	135	137.5	140	142.5	142.5
Fuel costs								
Average fuel price, lifetime	USD/MWh	177	140	122	100	83	69	57
Fuel costs	USD/year	44,366	35,065	30,483	25,037	20,658	17,139	14,310
Cost components								
Fuel costs	USD/MWh	413	289	226	182	148	120	100
Levelized fixed O&M (Operation and Maintenance) costs	USD/MWh	102	65	42	39	37	35	33
Levelized capital costs of discharging	USD/MWh	165	105	67	63	60	56	53
Levelized cost of hydrogen storage overall	**USD/MWh**	**680**	**459**	**334**	**285**	**244**	**212**	**187**

Figure 23: Levelized cost of hydrogen storage (production, storage, and utilization)

5.3 Remaining storage technologies

The discussion about the levelized cost of storage of ten different technologies (technologies other than hydrogen storage and lithium-ion battery) is included in this chapter. The same structure as lithium-ion battery technology is used for the calculations. The cost decrease scenarios are applied with the same percentages as well. However, some slightly different inputs and technology specific assumptions are made. The detailed calculation steps for low decrease scenario (10%) are represented in Appendix B. The technology specific assumptions regarding the inputs are:

- For all technologies, the analysis is initiated from 2020. The round trip efficiencies for 2020 are assumed to be the average values from the ranges in Figure 18. After 2020, the efficiencies for seven technologies are assumed to be increasing 10% (percent points) with the expectation of technology developments. For compressed air energy storage, the efficiency increase is assumed to be almost 20%, while for supercapacitors and superconducting magnetic energy storage, the efficiency is kept as a constant at 95%.

- Capital expenditures (capex) data for charging and discharging and for storage, as well as fixed operation and maintenance (O&M) costs for charging and discharging, are taken from Figure 18. They are assumed to be at the upper limit of the ranges. Since these data points are extracted from sources from different years and there is no estimation for future costs, for simplicity, these costs are used for 2020. After 2020, capital expenditures (costs) are assumed to be decreasing with three different scenarios (10%, 25%, and 50% in 10-year intervals). However, fixed operation and maintenance costs for charging and discharging are assumed to be constant up to 2050.

- Only for pumped hydro storage and compressed air energy storage, there is an extra cost input, fixed operation and maintenance cost for storage, is used. This data is collected from a report of International Energy Agency [31].

- Since there is no explicit information about what capital costs include, balance of plant (BOP) factor is taken as 1.2 (20% extra cost) for all technologies.

Based on above assumptions, the levelized cost of storage is calculated for the ten different technologies by using Equations (1) to (9). The results for three different scenarios are summarized in Figure 24. It is critical to realize that, for medium and high cost decrease scenarios, the only difference in calculations is assuming different percentages of decrease for capital expenditures after 2020.

Levelized cost of storage (LCOS) (USD/MWh)		Pumped Hydro Storage				Compressed Air Energy Storage				Liquid Air Energy Storage			
		2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050
Capital cost decrease scenarios	Low (10%)	125	106	96	86	204	155	142	129	331	279	251	226
	Medium (25%)	125	89	67	51	204	132	104	82	331	232	174	131
	High (50%)	125	60	31	17	204	94	56	37	331	155	77	39

Levelized cost of storage (LCOS) (USD/MWh)		Lead-acid Battery				Sodium Sulphur Battery				Nickel Cadmium Battery				Vanadium Redox Flow Battery			
		2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050
Capital cost decrease scenarios	Low (10%)	283	243	223	204	598	513	468	427	1089	922	831	750	608	517	471	429
	Medium (25%)	283	209	166	134	598	437	342	271	1089	771	582	440	608	440	343	271
	High (50%)	283	152	94	66	598	311	184	121	1089	519	267	141	608	311	182	118

Levelized cost of storage (LCOS) (USD/MWh)		Polysulfide Bromide Flow Battery				Supercapacitors				Superconducting Magnetic Energy Storage			
		2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050
Capital cost decrease scenarios	Low (10%)	746	628	565	509	633	571	514	463	3211	2892	2604	2345
	Medium (25%)	746	523	393	294	633	476	358	270	3211	2412	1812	1362
	High (50%)	746	349	174	87	633	319	162	83	3211	1612	813	413

Figure 24: Levelized cost of storage for three different capital cost decrease scenarios for ten technologies. *The figure shows levelized cost of storage for ten technologies in different years for three different capital cost decrease scenarios. Cost decrease scenarios are applied after 2020.*

In order to better interpret Figures 20-24, it is useful to tackle the cost results of each storage technology group separately. In mechanical storage category, it is clear that pumped hydro is the cheapest storage option with a cost of 125 USD/MWh in 2020 (Figure 24). Depending on the likelihood of all three cost decrease scenarios for each technology, there is a chance that compressed air energy storage may become cheaper than pumped hydro after 2030 or liquid air energy storage might be the cheapest one among the three of them by 2050. The applicability of one of the cost decrease scenarios can be mainly related to the maturity levels, in other words, the potential for further technology developments. For instance, since pumped hydro is one of the most mature storage technologies, this can indicate that there is not much space for further technology improvements or cost reductions. Hence, the low cost decrease scenario can be the only reasonable one for pumped hydro. On the other hand, the existing potential for efficiency increase in both compressed air energy storage and liquid air energy storage can make the medium or high cost decrease scenarios possible.

For electrochemical energy storage, lithium-ion battery is by far expected to be the least-cost storage technology throughout the future up to 2050 (Figures 20-24). With a low cost decrease scenario, levelized cost of storage for lithium-ion battery can fall from 134 USD/MWh in 2020, down to 44 USD/MWh in 2050 even though it might be unrealistic with the existing resource scarcity problems. Apart from lithium-ion battery, it is not likely to expect much or any cost reduction for lead-acid battery and nickel cadmium battery when the environmental concerns regarding these technologies are considered. These batteries might even be banned by many authorities in the future. Regarding sodium sulphur battery, it is highly possible to have an increase in the number of research studies about sodium use in the batteries since it is seen as a good alternative to lithium [26]. Therefore, the advancements in the performance of sodium based batteries could allow all 3 types of cost decrease scenarios to be applicable for sodium sulphur battery. With this assumption, its levelized cost of storage can fall down to 121 USD/MWh (Figure 24). As the last point, flow batteries might experience minor cost reductions in the short-term since there is a significant attention put on their research and development. Also, expecting high cost reductions may not be reasonable in the near future, because both flow battery technologies are still in the early development stages and they both (vanadium redox flow battery and polysulfide bromide flow battery) lack practical expertise. There can still be potential to decrease the levelized cost of storage from 608 USD/MWh in 2020 to the range of 118-429 USD/MWh in 2050 for vanadium redox flow battery and from 746 USD/MWh in 2020 to the range of 87-509 USD/MWh in 2050 for polysulfide bromide flow battery (based on the levelized cost of storage calculations).

Under electric and magnetic energy storage category, there is a vast difference between the levelized cost of supercapacitors and superconducting magnetic energy storage at any year with any cost decrease scenario (Figure 24). Due to its quite high capital investment cost, it is hard to predict major cost reductions for superconducting magnetic energy storage technology. There are also environmental concerns regarding the strong magnetic field that is being created with this technology. This would slow down any improvements regarding superconducting magnetic energy storage. Therefore, expecting big cost decrease, at least in the near future, may not be realistic. For supercapacitors, even though the cost of storage is relatively reasonable, for e.g. 633 USD/MWh in 2020, the cost reduction expectations will be shaped by the speed of the technological improvements. Because the technology is at the early stages of development and there are some urgent technical problems to be addressed, like high self discharge, before expecting any cost benefits.

6 Selecting technologies for further analyses

Available literature, as well as existing knowledge about energy storage trends indicate that hydrogen storage (including fuel cell) and lithium-ion battery are currently considered as two major energy storage technologies. Among their central advantages are their potential for supplying high energy density, and their reduced negative environmental impact, such as reduced greenhouse gas emissions, when compared to other technologies. This, together with the desire of the target company of this study, make further analyses essential on these two storage technologies.

Sensitivity analyses have been conducted in order to see the impact of the selected inputs. Such analyses help to identify the connections between independent variables and the research results which are dependent on the input variables. The impact that changing each individual variable would create on the results, while keeping other variables constant is observed. [52]

After sensitivity analyses, two models are created for lithium-ion battery in order to elaborate on the subjects of material availability and waste recycling value. Since resource scarcity is one of the biggest potential limitations against the developments in this technology, this study highlights these topics separately. Finally, hydrogen storage and fuel cell technologies are qualitatively evaluated from a safety and scalability point of view in order to give a better understanding about these relatively new (compared to lithium-ion battery, for example) concepts.

7 Sensitivity analyses

7.1 Lithium-ion battery

Based on the structure of the levelized cost of storage model in this study, round trip efficiency, annual charging times, lifetime, and capital expenditures (for storage) are assessed within sensitivity analyses. These four independent variables are paired in two different data tables in which the combined impact of them can also be seen. Then the analysis is followed by graphs that are showing the impact of four variables individually. The change in independent variables is shown in the x-axis, while the y-axis depicts the dependent variable which is the levelized cost of the storage. Year 2020 is chosen as the base year for the analyses. In this year, the value for the levelized cost of storage is predicted to be 134 USD/MWh.

In the first part of the analyses, annual charging times and round trip efficiency are paired in a single sensitivity table. Figure 25 shows the results for the levelized cost of storage when both variables are changed 5% at a time. The base cost value is 134 USD/MWh for 85% round trip efficiency and annual charging times of 365. Within the color scale, lowest (better) values are represented with the shades of green (the greener the color, the lower the value), while yellow and red colors stand for medium and high (worse) values, respectively.

As a next step, the effect of round trip efficiency and annual charging times is observed separately. Firstly, the round trip efficiency has been changed from 35% to 100% with 5% increments, while keeping annual charging times constant as 365. After that, the change of levelized cost of storage from the base value (134 USD/MWh) is calculated in percentages by using Equation 19. The same method is applied for the impact of annual charging times by keeping round trip efficiency constant as 85% and changing annual charging times with 5% increments in the range of positive and negative 50%.

$$\textit{Change in LCOS (\%)} = \frac{\textit{Final LCOS - Base LCOS}}{\textit{Base LCOS}} \times \textit{100} \tag{19}$$

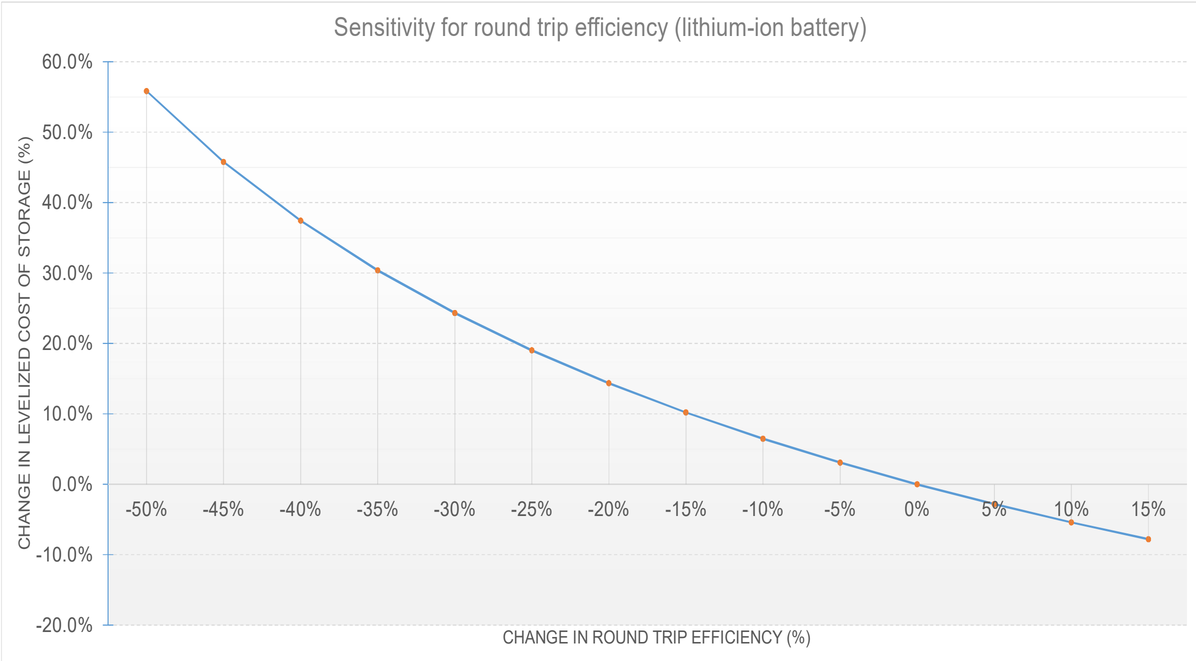
LCOS: Levelized cost of storage

The results for the sensitivity analyses of round trip efficiency and annual charging times are graphically shown in Figure 26. In both graphs, the levelized cost of storage reacts to the decrease of round trip efficiency and annual charging times by exponentially increasing. On the other hand, increasing these independent variables result in a decrease of the cost with a diminishing rate. In other words, in both graphs, the results show that the levelized cost of storage is more sensitive to the negative changes (decreasing the independent variables) than the positive changes (increasing the independent variables) since the curve on the negative side of the x-axis is steeper (higher slope) than on the positive side of the same axis. Also, levelized cost of storage is more sensitive to the changes in annual charging times than the changes in round trip efficiency.

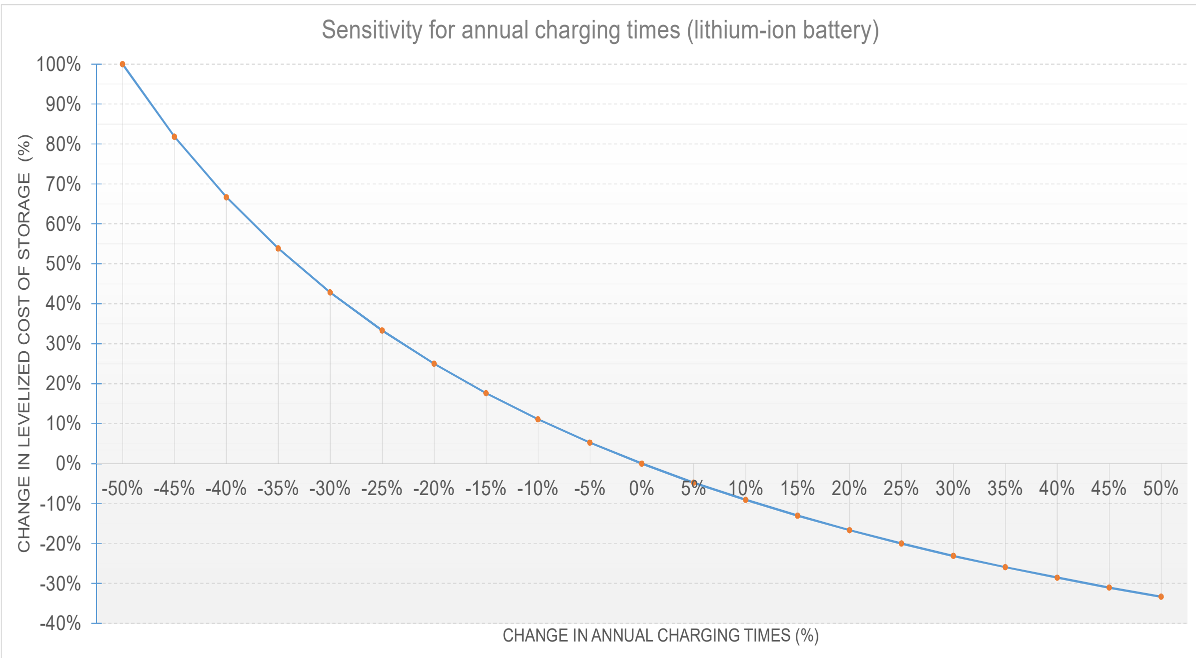
Sensitivity Analysis for Lithium-ion Battery (Round trip efficiency & Annual charging times)

Levelized cost of storage (LCOS) for 2020: 134 USD/MWh	Round trip efficiency													
Annual charging times	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%	100%
182.5	419	392	370	351	334	320	307	296	286	277	269	261	254	248
200.75	381	356	336	319	304	291	280	269	260	252	244	238	231	225
219	349	327	308	292	279	267	256	247	239	231	224	218	212	207
237.25	322	302	284	270	257	246	237	228	220	213	207	201	196	191
255.5	299	280	264	250	239	229	220	212	204	198	192	187	182	177
273.75	279	261	246	234	223	213	205	198	191	185	179	174	170	165
292	262	245	231	219	209	200	192	185	179	173	168	163	159	155
310.25	246	231	217	206	197	188	181	174	168	163	158	154	150	146
328.5	233	218	205	195	186	178	171	165	159	154	149	145	141	138
346.75	221	206	195	185	176	168	162	156	151	146	142	138	134	130
365	210	196	185	175	167	160	154	148	143	139	134	131	127	124
383.25	200	187	176	167	159	152	146	141	136	132	128	124	121	118
401.5	190	178	168	159	152	145	140	135	130	126	122	119	116	113
419.75	182	170	161	152	145	139	134	129	124	121	117	114	111	108
438	175	163	154	146	139	133	128	123	119	115	112	109	106	103
456.25	168	157	148	140	134	128	123	119	115	111	108	105	102	99
474.5	161	151	142	135	129	123	118	114	110	107	103	101	98	95
492.75	155	145	137	130	124	119	114	110	106	103	100	97	94	92
511	150	140	132	125	119	114	110	106	102	99	96	93	91	89
529.25	144	135	127	121	115	110	106	102	99	96	93	90	88	85
547.5	140	131	123	117	111	107	102	99	95	92	90	87	85	83

Figure 25: Sensitivity analysis with two variables for lithium-ion battery: round trip efficiency and annual charging times



a) Sensitivity analysis graph for round trip efficiency



b) Sensitivity analysis graph for annual charging times

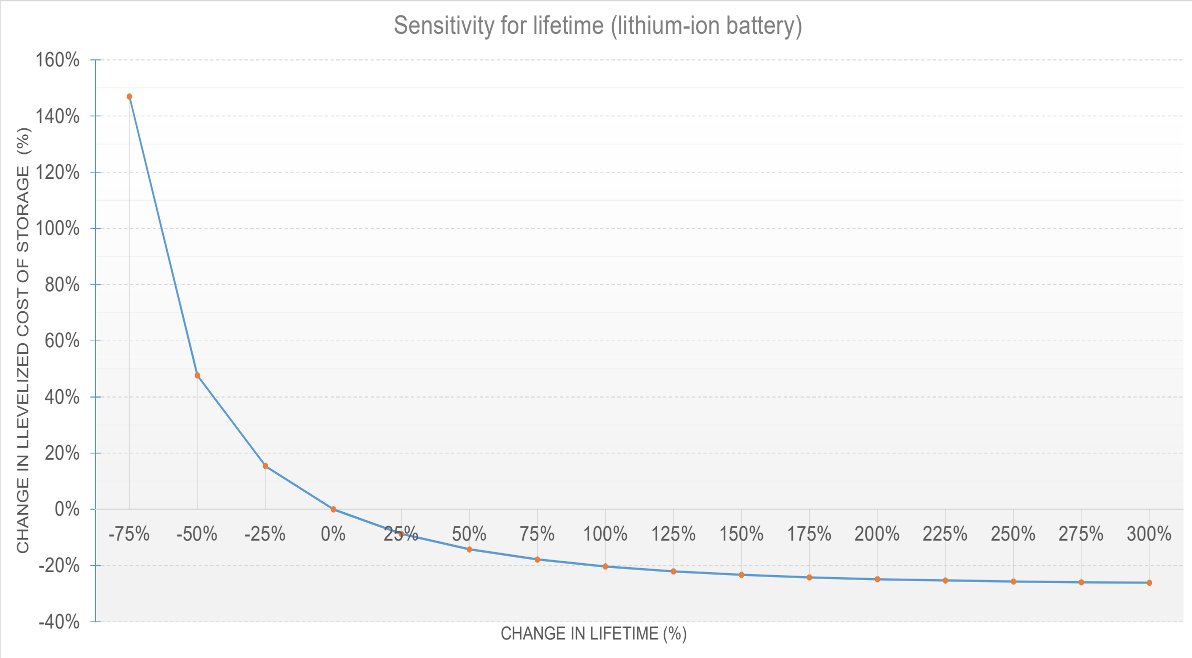
Figure 26: Sensitivity analysis graphs for lithium-ion battery: a) round trip efficiency and b) annual charging times. *For example, lowering round trip efficiency by 50% (from 85% to 35%) results in around 56% increase (from 134 to 210 USD/MWh) in levelized cost of storage, or increasing annual charging times by 50% (from 365 to 547.5) causes around 35% decrease (from 134 to 90 USD/MWh) in levelized cost of storage.*

In the second stage of the analyses, lifetime and storage capital expenditures (capex) are paired in the same sensitivity table (Figure 27). Both variables are changed with 25% increments at a time between -75% and 300%. The base value is 134 USD/MWh for a lifetime of 15 years and storage capital expenditures of 319 USD/kWh. Within the color scale, lowest (better) values are represented with the shades of green (the greener the color, the lower the value), while yellow and red colors stand for medium and high (worse) values, respectively.

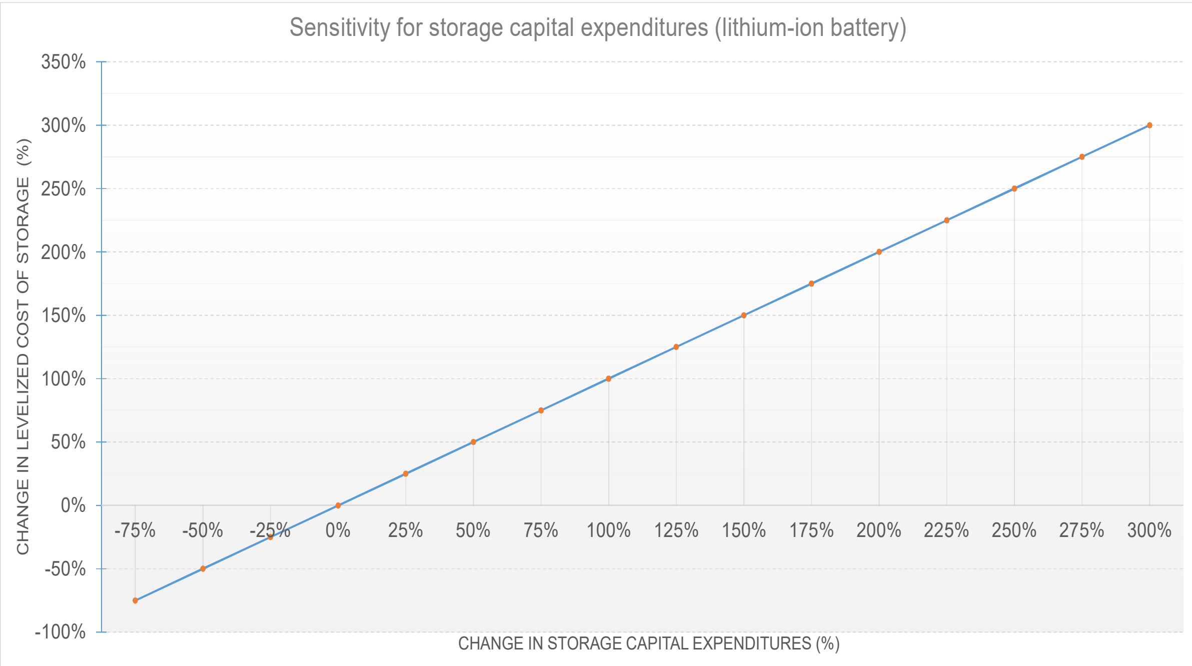
The change in levelized cost of storage in Figure 28 is calculated by using Equation 19. In the section a) of Figure 28, lifetime has an inverse effect to the levelized cost of the storage. Decreasing the lifetime causes the cost to increase, and vice versa. The cost is highly sensitive to the decreases in the lifetime, while the sensitivity reduces when the lifetime is increased. On the other hand, in the section b) of the same figure, storage capital expenditures have a direct and linear relationship with the cost. When the capital cost is decreased or increased, the levelized cost of storage also drops or increases with the same percentage. This shows that the levelized cost of storage is equally sensitive to both positive and negative changes in capital expenditures.

Levelized cost of storage (LCOS) for 2020	Sensitivity Analysis for Lithium-ion Battery (Lifetime & Storage capex)																
134 USD/MWh	3.75	7.5	11.25	15	18.75	22.5	26.25	30	33.75	37.5	41.25	45	48.75	52.5	56.25	60	Lifetime (years)
79.75	82	49	39	34	31	29	28	27	26	26	26	25	25	25	25	25	
159.5	163	98	77	67	61	58	56	54	53	52	51	51	51	50	50	50	
239.25	245	147	116	101	92	87	83	81	79	78	77	76	76	76	75	75	
319	326	197	155	134	123	116	111	108	106	104	103	102	101	101	101	100	
398.75	408	246	193	168	154	145	139	135	132	130	129	127	127	126	126	125	
478.5	489	295	232	202	184	174	167	162	158	156	154	153	152	151	151	150	
558.25	571	344	271	235	215	203	194	189	185	182	180	178	177	177	176	176	
638	652	393	309	269	246	232	222	216	211	208	206	204	203	202	201	201	
717.75	734	442	348	303	277	261	250	243	238	234	231	229	228	227	226	226	
797.5	816	492	387	336	307	290	278	270	264	260	257	255	253	252	251	251	
877.25	897	541	425	370	338	319	306	297	291	286	283	280	279	277	277	276	
957	979	590	464	403	369	348	333	324	317	312	309	306	304	303	302	301	
1036.75	1060	639	502	437	400	376	361	351	343	338	334	331	329	328	327	326	
1116.5	1142	688	541	471	430	405	389	378	370	364	360	357	355	353	352	351	
1196.25	1223	737	580	504	461	434	417	405	396	390	386	382	380	378	377	376	
1276	1305	787	618	538	492	463	445	432	423	416	411	408	405	404	402	401	
Storage capex (USD/kWh)																	

Figure 27: Sensitivity analysis with two variables for lithium-ion battery: lifetime and storage capital expenditures (capex)



a) Sensitivity analysis graph for lifetime



b) Sensitivity analysis graph for storage capital expenditures

Figure 28: Sensitivity analysis graphs for lithium-ion battery: a) lifetime and b) storage capex. *For example, lowering lifetime by 75% (from 15 years to 3.75 years) results in around 150% increase (from 134 to 387 USD/MWh) in levelized cost of storage, or increasing storage capital expenditures by 100% (from 319 to 638) causes 100% increase (from 134 to 269 USD/MWh) in levelized cost of storage.*

7.2 Hydrogen storage

Sensitivity analysis for hydrogen storage is concentrated on the production of hydrogen since this part contributes to the majority of overall levelized cost. From the production stage, two independent variables were selected by the target company to be included within the analysis: electricity price and annual production (Figure 29). These two variables are paired in a sensitivity table where they are both assumed to be increasing. The base year is 2020 with an electricity price of 0 USD/MWh and an annual production of 250 MWh/year resulting in an overall levelized cost of 680 USD/MWh. Annual production is increased with a constant value of 750 MWh/year, while electricity price is increased with 5 USD/MWh constantly. Within the color scale, lowest (better) values are represented with the shades of green (the greener the color, the lower the value), while yellow and red colors stand for medium and high (worse) values, respectively. The lowest cost is 308 USD/MWh when the electricity price is 0 USD/MWh and annual production is .

Sensitivity results are graphically presented in Figure 30 for annual production. Change in levelized cost is calculated by using Equation 19. Up to the point of 300% increase in production, there is a drastic decrease around 45% in the cost. However, after 300%, cost reduction is significantly slowing down so that it becomes almost fully flat after some point. This depicts that overall levelized cost is much more sensitive to the changes up to 300% in annual production than the further increases. Additionally, it is not possible to create such a graph for electricity price, which is the other independent variable, since the starting value is zero. However, it can be easily observed that there is a linear relationship between electricity price and overall levelized cost. By keeping annual production constant at 250 MWh/year, every 5 USD increase in electricity price results in 20 USD increase in levelized cost.

Levelized cost of storage (LCOS) for 2020	Sensitivity Analysis for Hydrogen Storage (Electricity price & Annual (hydrogen) production)														
680 USD/MWh	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
250	680	700	720	741	761	782	802	822	843	863	884	904	924	945	965
1000	389	394	399	404	409	415	420	425	430	435	440	445	450	455	460
1750	348	350	353	356	359	362	365	368	371	374	377	380	383	385	388
2500	331	333	335	337	339	341	343	345	347	349	351	353	355	357	360
3250	322	324	325	327	328	330	331	333	335	336	338	339	341	342	344
4000	316	318	319	320	322	323	324	325	327	328	329	330	332	333	334
4750	313	314	315	316	317	318	319	320	321	322	323	324	325	327	328
5500	310	311	312	313	314	314	315	316	317	318	319	320	321	322	323
6250	308	309	309	310	311	312	313	313	314	315	316	317	317	318	319
Annual production (MWh/year)	Electricity price (USD/MWh)														

Figure 29: Sensitivity analysis with two variables for hydrogen storage: electricity price and annual production

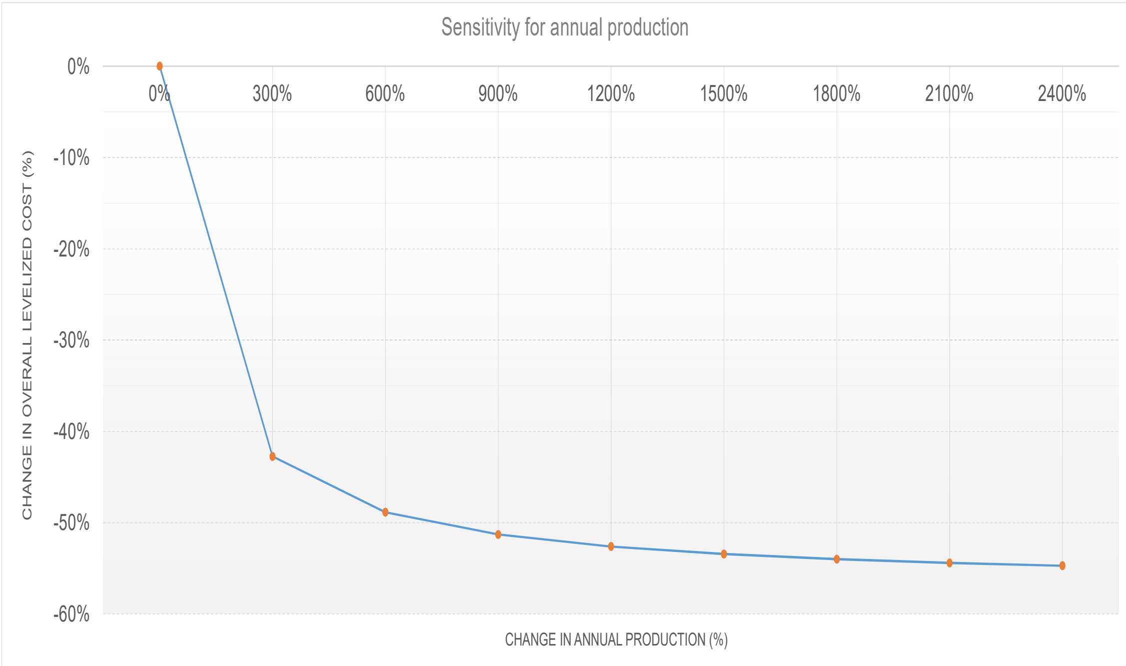


Figure 30: Sensitivity analysis graph for hydrogen storage (annual production). *For example, increasing annual production by 300% (from 250 to 1000 MWh/year) results in around 45% decrease (from 680 to 389 USD/MWh) in overall levelized cost.*

8 Sustainability and commercialization analyses

8.1 Lithium ion battery

8.1.1 Material availability

Resource scarcity is a critical topic for lithium-ion battery technology when the rapid growth in demand is considered. Cobalt (Co), nickel (Ni), aluminium (Al), and manganese (Mn) are some precious elements for the batteries since the cathodes formed with these materials provide the highest energy densities [44]. In addition to these elements, there are some other elements that are relevant for the lithium-ion battery sector. Those are iron (Fe), titanium (Ti), phosphorus (P), carbon/natural graphite (C), copper (Cu), and lithium (Li) [65]. Among all these elements, lithium and cobalt are the major bottlenecks or critical materials in the short-term [4, 44, 65].

Based on the above findings and the desire of the target company of this study, a critical analysis regarding material availability of lithium-ion battery is created in this chapter. Titanium, phosphorus, and copper are left outside of the scope of this analysis since the data regarding the material content of these elements is not being accessed. Initial step of the analysis is finding out the individual metal content of each battery chemistry in terms of ton/MWh (Figure 31)(changes in units done in the collected data for the sake of simplicity). An assumption regarding this data is that carbon (natural graphite) content is assumed to be the same for each chemistry since the sources where data is retrieved from have that value only for some of the chemistries.

Metals		Aluminum	Iron	Manganese	Nickel	Cobalt	Lithium	Natural Graphite
Symbols		Al	Fe	Mn	Ni	Co	Li	
Material Content								
NCA	ton/MWh	0.02			0.71	0.13	0.11	1.20
NCA+	ton/MWh	0.02			0.87	0.05	0.12	1.20
NMC (111)	ton/MWh			0.33	0.35	0.35	0.13	1.20
NMC (532)	ton/MWh			0.28	0.50	0.20	0.12	1.20
NMC (442)	ton/MWh			0.32	0.34	0.17	0.10	1.20
NMC (811)	ton/MWh			0.07	0.64	0.08	0.10	1.20
NMC (622)	ton/MWh			0.17	0.54	0.18	0.11	1.20
LFP	ton/MWh		0.67				0.08	1.20
LCO	ton/MWh					0.90	0.11	1.20
LMO	ton/MWh			1.42			0.09	1.20
Note: ton/MWh=kg/kWh								

Abbreviations:

NCA: Lithium Nickel Cobalt Aluminum Oxide (Bloomberg NEF refers an advanced form of NCA used by Tesla as NCA+)
NMC: Lithium Nickel Manganese Cobalt Oxide
LFP: Lithium Iron Phosphate
LCO: Lithium Cobalt Oxide
LMO: Lithium Manganese Oxide

Figure 31: Metal contents of different lithium-ion battery chemistries (natural graphite) [44], (other metals) [9]

In the second phase of the analysis, the data related to expected lithium-ion battery demand is required. Figure 32 shows the expected annual lithium-ion battery demand in four main categories: stationary storage, consumer electronics, e-busses, and passenger electric vehicles (EVs). Since the desired year for the analysis by the target company is 2050 and the lithium-ion battery demand data is forecasted up to 2030, a data projection is needed for the years between 2030 and 2050. In order to make this projection, compound annual growth rate (CAGR) is used.

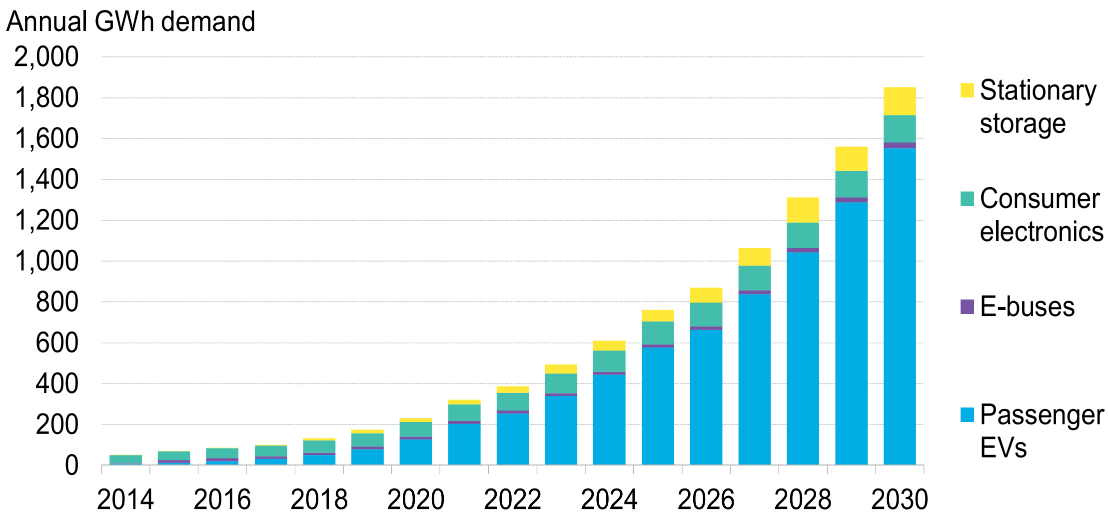


Figure 32: Expected annual lithium-ion battery demand [7]

Compound annual growth rate is a financial term and defined as "*the rate of return that would be required for an investment to grow from its beginning balance to its ending balance, assuming the profits were reinvested at the end of each year of the investment's lifespan*" [42]. However, it can also be used for calculating the average growth of a single value (the demand data in our analyses) when there is a volatile year-to-year growth rate [42]. Given this information and the data for the expected annual demand, compound annual growth rate for each category of lithium-ion battery demand is calculated from year 2017 to 2030 by using the below formula:

$$CAGR\ (Compound\ annual\ growth\ rate) = \left(\frac{Ending\ Value}{Beginning\ Value}\right)^{\left(\frac{1}{number\ of\ years}\right)} - 1 \tag{20}$$

Detailed information about the lithium-ion battery demand for each year and category is shown in Figure 33, section a) forecasted lithium-ion battery demand. These values are utilized in order to calculate the compound annual growth rate (CAGR) for each category, section b) compound annual growth rate (CAGR) values, by using Equation 20. Finally, the projection values are calculated by multiplying the previous year's data with (1+CAGR) for each consecutive year, section c) projected lithium-ion battery demand.

All values are in GWh	Year	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Passenger electric vehicles (EVs)		31	49	79	127	203	253	339	443	576	663	837	1,042	1,287	1,552
E-busses		13	13	13	14	14	14	15	15	16	17	19	21	25	29
Consumer electronics		54	60	66	72	80	88	95	104	112	116	121	125	129	133
Stationary storage		4	10	16	18	23	31	46	50	56	74	87	124	119	138
Total		101	132	173	231	321	386	495	611	760	871	1,063	1,312	1,560	1,851

a) Forecasted lithium-ion battery demand

Passenger electric vehicles (EVs)	CAGR	35%
E-busses	CAGR	7%
Consumer electronics	CAGR	7%
Stationary storage	CAGR	32%

b) Compound annual growth rate (CAGR) values

All values are in GWh	Year	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Passenger electric vehicles (EVs)		2,097	2,833	3,828	5,173	6,990	9,445	12,763	17,245	23,302	31,487	42,546	57,490	77,682	104,966	141,833	191,649	258,961	349,916	472,817	638,885
E-busses		31	33	35	37	39	42	45	48	51	54	58	61	65	70	74	79	84	90	96	102
Consumer electronics		143	153	164	176	189	202	217	232	249	267	286	307	329	353	378	406	435	466	500	536
Stationary storage		182	241	318	421	557	737	975	1,290	1,707	2,259	2,988	3,953	5,230	6,919	9,154	12,111	16,022	21,197	28,044	37,101
Total		2,452	3,260	4,346	5,807	7,775	10,427	14,000	18,816	25,310	34,067	45,878	61,811	83,306	112,308	151,440	204,244	275,503	371,670	501,456	676,624

c) Projected lithium-ion battery demand

Figure 33: Compound annual growth rate (CAGR) values and data projection: a) forecasted lithium-ion battery demand [7], b) compound annual growth rate (CAGR) values, and c) projected lithium-ion battery demand

As the next step, the share of demand of each category is calculated simply by dividing the demand of a category for a specific year into the total demand of that year. An assumption made for this calculation is including e-busses data under the passenger electric vehicles category due to the small fraction of first group of data (they are added up under passenger electric vehicles category for simplicity). Also, the percentages that are used in the model are only for years 2020, 2030, 2040, and 2050. The final results are gathered in Figure 34. The demand for lithium-ion battery will be drastically dominated by electric vehicle market.

GWh	Annual lithium-ion battery demand			
	Passenger electric vehicles (EVs) (including e-busses)	Consumer electronics	Stationary storage	**Total**
2020	140	72	18	231
2030	1,581	133	138	1,851
2040	31,541	267	2,259	34,067
2050	638,987	536	37,101	676,624

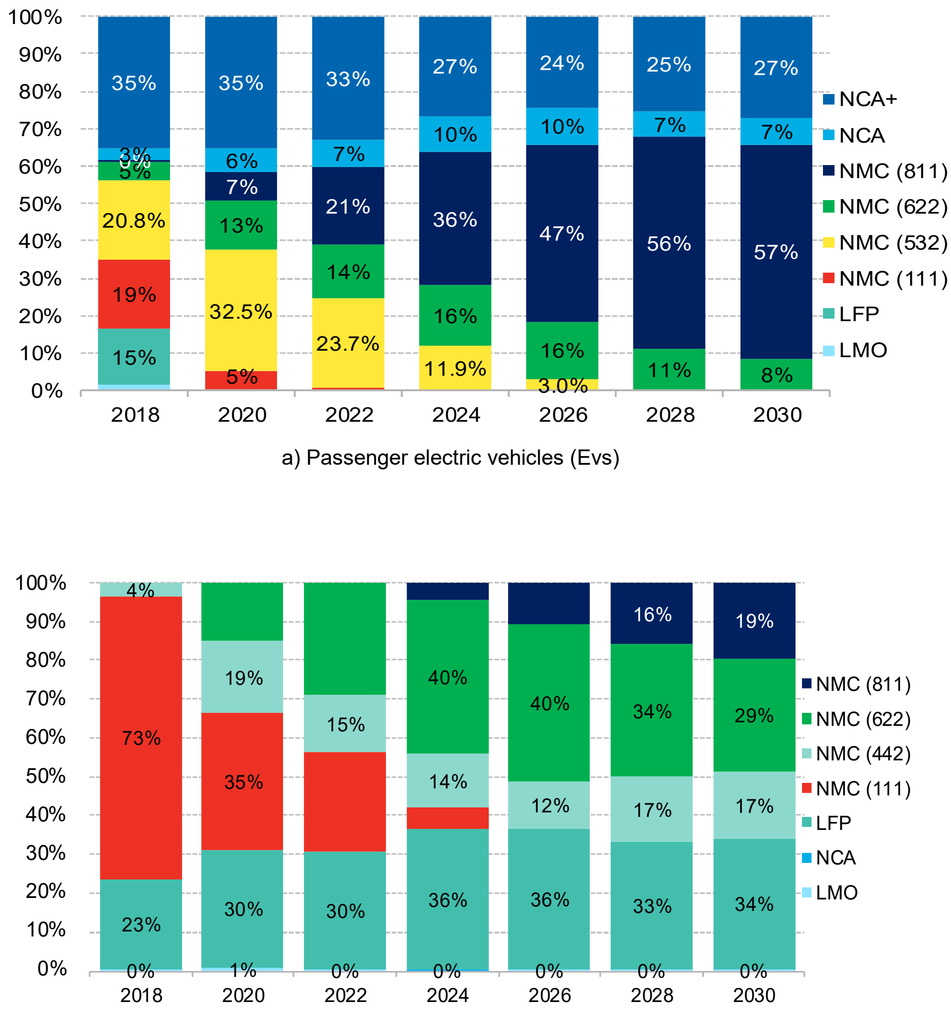
a) Lithium-ion battery demand

Share of each category	Year	2020	2030	2040	2050
Passenger electric vehicles (EVs) (including e-busses)		60.8%	85.4%	92.6%	94.4%
Consumer electronics		31.3%	7.2%	0.8%	0.1%
Stationary storage		8.0%	7.4%	6.6%	5.5%
Total		100%	100%	100%	100%

b) Share for each category

Figure 34: Lithium-ion battery demand and share for each category for years: 2020, 2030, 2040, 2050: a) lithium-ion battery demand and b) share for each category

In the final part of the data collection, the future trend of battery chemistry mix is gathered for passenger electric vehicles (EVs) and stationary storage (Figure 35). For consumer electronics, lithium cobalt oxide is assumed to be the sole chemistry due to lack of information from literature. This assumption is made based on the fact that this chemistry is commonly used in portable electronics [4, 44]. Since there is no forecast data accessed for years 2040 and 2050, the same chemistry mix as in year 2030 is assumed to be remaining after 2030 for passenger electric vehicles (EVs) and stationary storage categories while making the calculations in the later stages of the analysis.



a) Passenger electric vehicles (Evs)

b) Stationary storage

Abbreviations:

NCA: Lithium Nickel Cobalt Aluminum Oxide (Bloomberg NEF refers an advanced form of NCA used by Tesla as NCA+)
NMC: Lithium Nickel Manganese Cobalt Oxide
LFP: Lithium Iron Phosphate
LMO: Lithium Manganese Oxide

Figure 35: Battery chemistry mix [8]: a) passenger electric vehicles (EVs) and b) stationary storage

The essential part of the analysis is started by calculating the required amount of each individual metal (in terms of megaton) within each type of chemistry (Figure 36). For this purpose, firstly the expected demand for each chemistry is calculated by multiplying the demand forecast for each category (data from Figure 34) with the expected share of each chemistry (data from Figure 35). The same chemistry mix in year 2030 is assumed to continue after 2030. Finally, the forecasted demand (MWh) is multiplied with each chemistry's metal content (ton/MWh)(data from Figure 31) to find the required amount of each metal.

The analysis is followed by finding the total required amount of each metal. This is done by adding all the values for each metal. In order to make a comparison, the amount of available reserves for each material is identified. This data is obtained from the United States Geological Survey, Mineral Commodity Summaries 2019 [55]. After that, the availability factor is calculated by dividing the available amount by the required amount. Safety factor is assumed to be 10 to identify critical materials and the values bigger than this is shown as NA (not applicable). Based on this arrangement, by year 2040, it is found out that natural graphite, nickel, lithium, and cobalt are among the most critical materials with safety factors of 7.34, 3.90, 3.87, and 2.23, respectively. Figure 36 depicts the findings only for year 2040 since the safety factors are falling below 10 in this year. The results for year 2020, 2030, and 2050 are represented in Appendix A.

In the final stage of the analysis, the maximum capacity available as of 2040 is calculated based on the available amount of cobalt since it is the most critical material. In order to calculate this capacity, the demand in 2040 (around 34 million MWh) is multiplied with the availability factor of cobalt (2.23), which results in around 76 million MWh of capacity. When this number is compared to the projected demand forecasts in Figure 33, year 2042 is identified as the latest year that can be reached with the maximum available capacity. In other words, the fact that the demand will be above 83 million MWh in year 2043 shows that the available capacity will come to an end between 2042 and 2043.

Metals		Aluminium	Iron	Manganese	Nickel	Cobalt	Lithium	Natural Graphite	Expected chemistry		Capacity forecast 2040	
Symbols		Al	Fe	Mn	Ni	Co	Li		2020	2030, 2040 ,2050	MWh	Share of each category
Required material												
Passenger electric vehicles (EVs) (including e-busses)												
NCA	megaton	0.0442	0.00	0.00	1.57	0.287	0.243	2.65	6%	7%	2,207,877	
NCA+	megaton	0.1703	0.00	0.00	7.41	0.426	1.02	10.22	35%	27%	8,516,098	
NMC (111)	megaton	0.0000	0.00	0.000	0.000	0.000	0.000	0.00	6%		0	
NMC (532)	megaton	0.0000	0.00	0.00	0.00	0.000	0.00	0.00	33%		0	
NMC (442)	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0	
NMC (811)	megaton	0.00	0.00	1.28	11.71	1.464	1.829	21.95	7%	58%	18,293,839	
NMC (622)	megaton	0.00	0.00	0.43	1.36	0.454	0.278	3.03	13%	8%	2,523,288	
LFP	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0	
Total	**megaton**	**0.21**	**0.00**	**1.71**	**22.05**	**2.63**	**3.37**	**37.85**	100%	100%	31,541,102	92.6%
Consumer electronics												
LCO	megaton	0.00	0.00	0.00	0.00	0.24	0.03	0.32	100%	100%	267,106	
Total	**megaton**	**0.00**	**0.00**	**0.00**	**0.00**	**0.24**	**0.03**	**0.32**	100%	100%	267,107	0.8%
Stationary storage												
NCA	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0	
NCA+	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0	
NMC (111)	megaton	0.00	0.00	0.000	0.000	0.000	0.000	0.00	35%		0	
NMC (532)	megaton	0.00	0.00	0.00	0.00	0.000	0.000	0.00			0	
NMC (442)	megaton	0.00	0.00	0.123	0.131	0.065	0.0384	0.461	20%	17%	383,975	
NMC (811)	megaton	0.00	0.00	0.0300	0.275	0.034	0.0429	0.515		19%	429,149	
NMC (622)	megaton	0.00	0.00	0.1114	0.354	0.1179	0.0721	0.786	15%	29%	655,017	
LFP	megaton	0.00	0.530	0.00	0.00	0.00	0.0632	0.95	30%	35%	790,537	
Total	**megaton**	**0.00**	**0.530**	**0.264**	**0.759**	**0.218**	**0.217**	**2.71**	100%	100%	2,258,678	6.6%
Summary												
Grand Total Required	megaton	0.21	0.53	1.97	22.81	3.09	3.62	40.88			34,066,886	100%
Total Material Available	megaton	30,000	170	760	89	7	14	300				
Available factor (Available/Required)	-	NA	NA	NA	**3.90**	**2.23**	**3.87**	**7.34**				
Maximum capacity available											**76,110,252**	

Figure 36: Material availability calculations for 2040 (chemistry mix based on [8], demand forecast based on [7], available reserves [55])

8.1.2 Energy density improvements

The material availability problem, as being an essential part of sustainability issues, stems initially from performance considerations. One of the most important properties of lithium-ion batterY is having high energy density which rapidly made this technology commercial. So far, high energy density has been achieved with the help of some elements like cobalt (Co) which brings us back to the topic of limited availability of necessary resources. Improving energy density by utilizing mainly abundant elements has been practiced with recently emerging technologies. This is also critical to achieve economies of scale in manufacturing, and therefore gradual cost reductions.

Sodium-ion battery is an important alternative technology to lithium-ion battery. This is due to the fact that sodium has similar chemical properties with lithium and it is extensively available in Earth's crust and sea water. [26, 33]However, the molecular weight of sodium is more than three times than of lithium [33]. This can cause some trouble for electric vehicle applications where the weight of the storage unit has a great importance, while it would create not much difference for grid storage applications. Additionally, in order to manage better performance goals with sodium-ion battery, it is critical to excel in suitable electrolytes by discovering new binders, additives, and solvents [26, 33].

Lithium sulphur battery and lithium air battery are two types considered as post lithium-ion technologies. The first one utilizes sulphur as the active material. Sulphur is highly available at low cost and provides superior energy density of up to 400 Wh/kg. Lithium sulphur battery is also safer than lithium-ion battery due to its chemical structure. However, high self-discharge rate and very low cycle lifetime (50-100 full cycles) are major hurdles that prevents this technology from being commercially viable. [27] The latter technology, by utilizing oxygen, provides the highest theoretical energy (10 times higher than the market average) and power density compared to all other battery technologies [27, 33]. On the other hand, lithium air battery technology suffers from environmental conditions, particularly humidity, as well as low storage capacity [27]. In addition, Olivetti et al. [44] mention that both of these post lithium-ion technologies, compared to current commercial lithium-ion battery, may use double amounts of Li per kWh of stored energy because of their lower cell voltage.

8.1.3 Recycling

The ability to be recharged easily and providing high energy density have caused lithium-ion battery usage grow rapidly [61]. Average lifetime of a lithium-ion battery for consumer products is 3 years [32], and 10 years for plug-in hybrid electric vehicles [38]. Rapid growth in demand and limited lifetime of lithium-ion battery have created material availability problem and drawn the attention to the importance of recycling of used lithium-ion batteries due to the increasing battery waste stream [58].

Considering the levels of recycling efficiencies in Figure 38, this study tackles the recycling matter by putting the emphasis on the economics aspect of the process. An analysis of the value of recycling business has been made for evaluating economic viability of recycling. Before describing the analysis, it is useful to briefly introduce the general recycling process. A usual recycling process includes the combination of physical and chemical processes. Pretreatments (crushing, screening, washing, dismantling etc.) belong to the physical steps while pyrometallurgical and hydrometallurgical methods (extraction, leaching, separation etc.) are chemical processes. Thanks to these processes, it is possible to recover (some) cathode metals like lithium, manganese, cobalt etc. with high purity which then can be utilized as a source of raw materials for new batteries. [25]

The recycling analysis is initiated with the data regarding the amount of used lithium-ion batteries that will end up in the waste stream. Figure 37 presents the data for potential amount of used lithium-ion batteries both in total and for electric vehicles separately in year 2025, section a) lithium-ion battery waste data. These numbers are gathered, by Winslow et al. [61], based on the approximate number of units of lithium-ion battery devices sold for different applications worldwide in 2016. The figure also shows data for a base case recycling facility, section b) data for existing recycling facilities. Additionally, yearly waste amount is calculated by simply dividing the total expected waste by nine since the waste is assumed to be accumulating within nine years. Finally, the share of electric vehicles is also estimated (54%) in order to forecast the market value for only electric vehicles in the end. It is forecasted that electric vehicles will account for the biggest share of waste lithium-ion batteries in the future [61].

Expected total LIB waste between 2016-2025	metric ton	374,000
Expected yearly LIB waste based on 9 years timeline	metric ton/year	41,556
Expected electric vehicle (EV) LIB waste between 2016-2025	metric ton	203,000
Share of EV LIB waste	%	54%

a) Lithium-ion battery (LIB) waste data

Fixed costs	USD/year	1,000,000
Variable costs	USD/metric ton	2,800
Maximum working capacity	metric ton/year	33,900

b) Data for existing recycling facilities

Figure 37: Lithium-ion battery (LIB) recycling data: a) lithium-ion battery (LIB) waste data [61] and b) data for existing recycling facilities [58]. *In section a), expected lithium-ion battery waste data, within nine years, is collected both in total and for electric vehicles separately. Based on this data, yearly waste amount and share of electric vehicles are calculated. Section b) represents cost data for existing recycling facilities with a maximum working capacity of 33900 metric ton/year.*

In the second phase of the analysis, market prices of the valuable metals and recycling efficiencies are gathered. Equal share of waste percentages is assumed for all metals (17% of 374,000 metric tons of lithium-ion battery waste). After that, yearly waste amount and yearly potential recycled amount of each metal is calculated by using 17% equal waste share and recycling efficiencies. Yearly data is calculated by simply dividing the total amount by nine since the waste amount is estimated to occur between 2016 and 2025.

Metals		Aluminium	Manganese	Nickel	Copper	Cobalt	Lithium
Symbols		Al	Mn	Ni	Cu	Co	Li
Metal prices	USD/metric ton	1,885	2,060	8,932	5,720	80,490	16,500
Recycling efficiency	%	42%	53%	62%	90%	89%	80%
Assumed metal concentration of the waste	%	17%	17%	17%	17%	17%	17%
Total waste metal amount available for recycling	metric ton (in thousands)	62	62	62	62	62	62
Yearly waste metal amount available for recycling	metric ton/year (in thousands)	7	7	7	7	7	7
Total potential recycled metal amount	metric ton (in thousands)	26	33	39	56	55	50
Yearly potential recycled metal amount	metric ton/year (in thousands)	3	4	4	6	6	5

Total variable cost	USD/year (in millions)	116
Total fixed cost	USD/year (in millions)	1
Total cost	USD/year (in millions)	**118**
Total potential revenue	USD/year (in millions)	**675**
Total potential profit	USD/year (in millions)	**557**
Minimum amount to be recycled to cover total cost	metric ton/year (in thousands)	**7**
Total revenue cross check at breakeven point	USD (in millions)	**118**
Potential revenue by 2025 (for all LIB waste)	USD (in billions)	**6**
Potential revenue by 2025 (for EV LIB waste)	USD (in billions)	**3**

Figure 38: Economics of lithium-ion battery recycling (Metal prices [39], Recycling efficiencies (gathered by Wang et al. [58] from different resources))

The analysis continues by computing cost and revenue (Figure 38) data based on the data in Figure 37, metal prices, and yearly potential recycled metal amount. Total variable cost is calculated by multiplying variable costs (2,800 USD per metric ton) with yearly waste amount (41,556 metric ton per year). Total fixed cost is calculated as the following: (41,556/33,900)×1,000,000. Total potential revenue is computed as the sumproduct of metal prices and yearly potential recycled metal amount. This shows that there is as high as around 557 million dollars profit potential yearly. After that, the minimum yearly amount of lithium-ion battery waste to be recycled is calculated by dividing total yearly cost by the sumproduct of metal prices, recycling efficiencies, and assumed metal concentration of the waste. In order to validate the result as a breakeven point, total revenue is calculated based on this minimum amount of waste to be recycled. Finally, total potential revenue by 2025 is calculated by multiplying yearly value with nine. This revenue is also translated into the value of waste extracted from electric vehicles by using the share of 54% (Figure 37). This calculation shows that there is a revenue potential of more than 3 billion dollars by 2025 for waste recycling from electric vehicles. It is reassuring for the analysis to see that this value is close to the estimate of 2 billion dollars by 2022 which is predicted by some other forecasts made for the electric vehicle lithium-ion battery recycling market [44].

The analysis of the battery recycling market is limited in the sense that it does not take into account the different waste amount of different battery cathode chemistries (as well as the individual metal content inside each disposed chemistry). With a more detailed approach, it can be predicted that the price of each metal can vary even depending on the country due to the recycling market demand in different regions. The scrap metal prices might be remarkably different than the prices of the metals coming from mines. Moreover, recycling efficiencies might significantly differ depending on the method of recycling. With recent improvements in technology, higher recovery efficiencies can be obtained. Last but not the least, capacity and cost data can easily change from one facility to the other one depending on the country, local legislation, and technical advancements within the facility.

8.2 Hydrogen storage

Hydrogen is considered as a good green alternative to fossil fuels since it can be produced by environmentally friendly methods. It can significantly lower emission of harmful gases (water is the only byproduct of hydrogen combustion). Hydrogen can become the future source of energy. However, there are still some safety issues regarding hydrogen's high inflammability and high potential of leakage through different materials. These problems are affecting the speed of commercial expansion of hydrogen utilization. Hydrogen has a low minimum ignition energy of 0.017 mJ. Moreover, to measure hydrogen concentration and to detect any leakage, sensors are essential during the whole journey of hydrogen from production facilities to the storage tanks/caverns and refueling stations. Hydrogen can not be recognized by human beings' natural ability due to its colorless, tasteless, and scentless nature. [16]

Whereas further attention is put on underground storage of hydrogen as being the cheapest and the most suitable option for stationary storage, there are remarkable advantages compared to above ground storage. Underground storage allows storage in large volumes with higher pressures (high pressure is increasing the amount of stored hydrogen [48]). Also, underground storage is considered to be safer and requiring smaller space. [45]

Underground storage also has some critical aspects to be carefully evaluated in order to achieve high level of efficiency and scalability. For instance, the risk of leakage in hydrogen storage is bigger than the risk is in natural gas storage [45]. For this reason, it is important to be aware of the geological structure of the caverns (for e.g. permeability) even if the same storages had previously been used as a natural gas storage. Among different rock types, rock salt has one of the lowest permeability compared to, for example, granite or clay [50]. Another criteria is finding the suitable rock salt cavern with an adequate thickness and sufficient level of depth. It is also possible to build artificial caverns by using the right mining techniques. [45] In addition to this, hydrogen quality (the level of purity) might be affected from the material of the caverns. Hydrogen sulfide or water vapor are some of the impurity examples. In such cases, some extra treatments such as drying and purification are needed before injecting hydrogen into a pipeline. [48]

Storage is an important part of the transition for using hydrogen as one of the major energy sources. Therefore, in order to accelerate its commercialization with efficiency, practicing the best methods and taking the right precautions are extremely vital. Otherwise, especially in large scales, severe safety accidents like explosions due to high pressure might occur.

8.3 Fuel cells

Constructing the future energy supply on hydrogen storage requires efficient ways of utilization of hydrogen. Fuel cell technology is considered as one of the most efficient and cleanest methods for using hydrogen as the fuel source [56, 60]. That is why, hydrogen storage and fuel cell technology can not be tackled separately even though it is possible to use another source of fuel within a fuel cell. This, together with the target company's interest on identifying the barriers of commercialization for fuel cells, make this study concentrate further on fuel cell technology.

Stationary fuel cell technology, which is the main focus of this study, is the most preferable type of different applications in this sector. Despite the fact that fuel cell technology is already commercially employed and it has many advantages over conventional combustion engines (higher efficiency, less noise and vibration etc.), there are certain barriers that are slowing down the process of scaling up. These barriers include cost, durability, and reliability related matters. [60]

Cost is a challenge preventing the expansion of fuel cell technology. Cost benefits in terms of manufacturing have not yet been achieved compared to internal combustion engines. On the other hand, it is possible to obtain less operational costs with fuel cells than engines thanks to high thermal efficiency. Cost problem is also correlated with reliability and durability of the technology. Due to low reliability and durability of fuel cell technology, total costs might significantly be increased as a result of unexpected maintenance costs. [56, 57]

In terms of reliability and durability, these factors are mainly connected to the performance of a fuel cell. Fuel cell systems include stacks that include many individual cells. Any unexpected failure in the cell level causes problems in the whole stack which is a major challenge for scaling up the manufacturing of fuel cell systems. Individual cells might fail easily because of a malfunctioning or broken component such as a membrane or gas diffusion layer. Any component failure induces remarkable cost increases due to required extra processes like balancing of the stack, conditioning, and assembly. [57]

In order to manage commercialization in large scales, reliability and durability problem should be handled at the initial design stages (design of the cell). The worst performing individual cell determines the characteristics (such as lifetime, reliability, and durability) of a fuel cell stack. Optimization of flow conditions (flow rates, humidity, pressure, temperature etc.) and solving the fundamental problems of cell components such as corrosion, weak water management, fuel and oxidant starvation, flooding etc. are key challenges in increasing reliability and durability of the fuel cell technology. Achieving uniform design conditions for each cell is essential to prevent failures in the stacks and to scale up fuel cell technology successfully. [56] All in all, fuel cell scalability is an important factor in increasing hydrogen storage and in encouraging the transition towards hydrogen as a fuel in the energy sector. Being able to create a secure business opportunity for the utilization of hydrogen will definitely motivate companies more to produce and store hydrogen in large amounts.

9 Reliability and validity analysis

Validity in research studies is concerned with the extent to which an instrument of research is in fact measuring what it is meant to evaluate [30]. Reliability in research studies attributes to the stability of data collection techniques. Stability is attained if another researcher conducting the same analyses in a different time with the identical techniques to the previous researcher, obtains consistent results with the former work [30, 35]. This definition of stability is referred as the absence of random error in the study of Gibbert et al. [23]. Transparency is one of the most important methods of achieving stability. It refers to cautious documentation and defining the research procedures explicitly [23]. In this current study, the steps and assumptions regarding each analysis are detailed in appropriate chapters. The source for each data point is clearly mentioned and input data points are logically implemented into the models. Additionally, in order to increase the reliability of the analysis and comparisons made, many important factors have been taken into consideration. For instance, the environmental impact of the technologies is considered by addressing resource scarcity. Technological factors are taken into account, by including state of the art applications and technical aspects of the storage technologies. Market factors are additionally considered, by using estimates of cost trends, efficiency improvements, demand forecasts, and technology expectations. Finally, economic factors are underlined by creating cost models based on realistic assumptions and conducting supportive sensitivity analyses. Finally, detailed literature survey and qualitative discussions are utilized to increase credibility of this study. Gathered information has been validated from several resources and useful discussions are created.

A few factors have been omitted from the scope of this study, and can be considered as limitations and grounds for future studies. For instance, there are some geographical factors that have not been taken into account. Based on the country or location, the models created in this study would have differed. The landscape and the demographic conditions would affect the cost and viability of the storage technologies. In parallel with this, the demand for power varies based on the population, thereby changing the selection criteria for the most suitable technology. Additionally, the cost of the materials and construction requirements would differ based on the economic condition and the expertise available in different countries. The legislation and future energy plans of a certain country could influence which technology would be the most suitable there. The impact of emissions has also been omitted from the scope of this study. Analyzing how much actual emission reduction is possible with such technologies would be worth considering as part of the environmental impact. Costs that are deduced from environmental impact would also add serious indirect costs to the initial capital or maintenance costs, and as a result, levelized cost of storage would be affected.

10 Conclusions

This work analyzes the technical features of twelve different energy storage technologies. The main conclusions follow from qualitative analyses, levelized cost of storage analyses, sensitivity analyses of lithium-ion battery and hydrogen storage, material availability analysis of lithium-ion battery, and scalability analyses of hydrogen storage and fuel cell technology. From the qualitative analysis, it can be concluded that there is no single technical viability criterion. Different applications will favor different characteristics of each technology, which will determine its technical viability level. For instance, pumped hydro storage is technically viable for seasonal storage applications due to its very small self-discharge rate. However, for short-term storage of less than a month, pumped hydro can become infeasible. This is primarily due to its low round trip efficiency when compared to lithium-ion battery for example, and due to long break even time of the projects. Additionally, there are strict geographic restrictions for the construction of a pumped hydro system, and it is also a highly mature technology with little space for further technical advancements. Technologies with high self-discharge rate like supercapacitors (20-40%) and superconducting magnetic energy storage (10-15%) are suitable only for energy shifting applications of maximum one day. Lithium-ion battery, as a commercially proven technology, provides two of the most desirable features of a storage system. Firstly, it has the highest actual specific energy from all available technologies, and secondly it can provide high round trip efficiency. With flow batteries and hydrogen storage, which are recently developing concepts, it would be quite expensive to achieve the same or better performance in terms of specific energy and round trip efficiency.

The results of levelized cost of storage analyses show that lithium-ion battery technology will continue to be the cheapest energy storage option in 2050. Levelized cost of storage for lithium-ion battery can drop below 50 USD/MWh depending on the level of capital cost reductions. Levelized cost of hydrogen storage, including production, underground storage, and discharging with fuel cells, can become less than 200 USD/MWh in 2050. This is despite the fact that the cost in 2020 is around 700 USD/MWh. In Figure 23, production cost (fuel costs) of hydrogen is addressed as the highest cost contributing to overall levelized cost of hydrogen storage. The second highest cost is identified as discharging (fuel cell) costs. Finally, in Figure 24, pumped hydro storage is realized as the most cost competitive technology compared to lithium-ion battery. Levelized cost of pumped hydro storage is also expected to reach to the levels below 100 USD/MWh.

In the sensitivity analyses of lithium-ion battery, levelized cost of storage is more sensitive to changes in annual charging times than the changes in round trip efficiency. In addition to this, lowering the lifetime has a bigger impact on levelized cost than increasing the lifetime. Finally, changes in capital costs affect levelized cost of storage linearly. As for hydrogen storage, increasing electricity price increases levelized cost proportionally. Additionally, increasing annual production has a great negative impact on levelized cost. However, the impact reduces drastically after a certain point. The underlying reason is that annual production affects levelized cost of production, and therefore fuel costs. Initial increases in annual production decrease this production cost significantly. The more extreme the increase in annual production becomes, the smaller its effect on levelized cost of production becomes.

The material availability analysis shows that, based on the expected demand of lithium-ion battery and the material content of each chemistry, the existing reserves will become critical in 2042 for the following materials, listed in the order of their importance level: cobalt, lithium, nickel, and natural graphite. This resource scarcity problem can be overcome by replacing the critical materials with other ones that could provide the same performance. In that sense, sodium-ion battery is one of the best alternatives to lithium-ion battery due to similar chemical properties of sodium and its high abundance in nature. Another possible way to deal with the material problem is to recycle waste lithium-ion batteries. The calculations for the economics of recycling market show that there is a revenue potential of around 6 billion dollars by 2025, of which more than half is attributed to the recycling of waste batteries from electric vehicles. The recycling model in this study shows that recycling is economically viable based on the recycling degree of important materials of lithium-ion battery.

Last but not the least, hydrogen is one of the best clean energy alternatives to fossil fuels. This emphasizes the importance of hydrogen storage as well as the safety problems related to this technology such as inflammability and leakage. These problems exist both in underground and above ground storage, and they impede scalability of the technology and reduce its efficiency. Improving the design of the tanks for above ground storage, and practicing the best methods for maintaining hydrogen quality in salt caverns for underground storage are key factors for the expansion of hydrogen storage. For the utilization of the stored hydrogen, fuel cell technology should additionally be taken into consideration. High manufacturing costs and unstable design conditions are among the major important problems that prevent the commercialization of fuel cell technology.

11 Recommendations for future studies

This study will encourage researchers to initiate further analyses about various aspects of storage technologies. One of the most interesting subjects to investigate would be hybrid energy storage solutions. Different technologies have several complementary features that can create positive synergies. This would also increase the flexibility and reliability of storage systems with improved capabilities. One potential combination can be lithium-ion battery and supercapacitors, for example. Supercapacitors can provide fast response for surge electricity demand due to its extremely high power density. However, further research can also study the financial aspects of combining different technologies to find out its economic viability. Identifying potential benefits and threats would help organizations to start investing in such hybrid solutions and perhaps improve their ability to control increasing energy demand.

Further steps can include a specific perspective for only environmental impacts of storage technologies. Starting from their installment/construction till the point of their utilization and decommissioning, environmental concerns can be highlighted. Although storage technologies might seem to be environmentally friendly, any potential negative implications should be identified. For instance, any type of battery waste could be harmful for the environment due to their chemical components unless they are treated (recycled) properly. This can also enable studying innovative and sustainable concepts such as biocells.

In order to gain more knowledge about the state of the art technologies or the most up to date storage applications, one can research the existing patents both for storage and recycling systems. Being well informed about patent applications would allow detecting recent technical developments and assessing whether the expected/required progress for a particular technology has actually happened or not. This would also enable significant cost reductions both in capital investments and maintenance expenses since it increases the ability to take preventive actions. Finally, patent analysis can ultimately bring competitive advantage to any organization by increasing its awareness against potential threats. A company can better anticipate the future trends and prepare its set of actions accordingly.

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A Material availability calculations for 2020, 2030, and 2050

Metals		Aluminium	Iron	Manganese	Nickel	Cobalt	Lithium	NAtural Graphite	Expected chemistry		Capacity forecast 2020	
Symbols		Al	Fe	Mn	Ni	Co	Li		2020	2030, 2040 ,2050	MWh	Share of each category
Required material												
Passenger electric vehicles (EVs) (including e-busses)												
NCA	megaton	0.0002	0.00	0.00	0.01	0.001	0.001	0.01	6%	7%	8,418	
NCA+	megaton	0.0010	0.00	0.00	0.04	0.002	0.01	0.06	35%	27%	49,106	
NMC (111)	megaton	0.0000	0.00	0.003	0.003	0.003	0.001	0.01	6%		8,418	
NMC (532)	megaton	0.0000	0.00	0.01	0.02	0.009	0.01	0.06	33%		46,300	
NMC (442)	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0	
NMC (811)	megaton	0.00	0.00	0.00	0.01	0.001	0.001	0.01	7%	58%	9,821	
NMC (622)	megaton	0.00	0.00	0.00	0.01	0.003	0.002	0.02	13%	8%	18,239	
LFP	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0	
Total	**megaton**	**0.001**	**0.00**	**0.02**	**0.09**	**0.02**	**0.02**	**0.17**	100%	100%	140,303	60.8%
Consumer electronics												
LCO	megaton	0.00	0.00	0.00	0.00	0.06	0.01	0.09	100%	100%	72,200	
Total	**megaton**	**0.00**	**0.00**	**0.00**	**0.00**	**0.06**	**0.01**	**0.09**	100%	100%	72,200	31.3%
StatioNAry storage												
NCA	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0	
NCA+	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0	
NMC (111)	megaton	0.00	0.00	0.002	0.002	0.002	0.001	0.01	35%		6,436	
NMC (532)	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0	
NMC (442)	megaton	0.00	0.00	0.001	0.001	0.001	0.0004	0.004	20%	17%	3,678	
NMC (811)	megaton	0.00	0.00	0.0000	0.000	0.000	0.0000	0.000		19%	0	
NMC (622)	megaton	0.00	0.00	0.0005	0.001	0.0005	0.0003	0.003	15%	29%	2,758	
LFP	megaton	0.00	0.004	0.00	0.00	0.00	0.0004	0.01	30%	35%	5,517	
Total	**megaton**	**0.001**	**0.004**	**0.004**	**0.005**	**0.003**	**0.002**	**0.02**	100%	100%	18,389	8.0%
Summary												
Grand Total Required	megaton	0.001	0.004	0.02	0.10	0.09	0.03	0.28			230,892	100%
Total Material Available	megaton	30,000	170	760	89	7	14	300				
Available factor (Available/Required)	-	NA	NA	NA	NA	NA	NA	NA				
Maximum capacity available											**NA**	

Metals		Aluminium	Iron	Manganese	Nickel	Cobalt	Lithium	NAtural Graphite	Expected chemistry		Capacity forecast 2030	
Symbols		Al	Fe	Mn	Ni	Co	Li		2020	2030 2040 ,2050	MWh	Share of each category
Required material												
Passenger electric vehicles (EVs) (including e-busses)												
NCA	megaton	0.0022	0.00	0.00	0.08	0.014	0.012	0.13	6%	7%	110,636	
NCA+	megaton	0.0085	0.00	0.00	0.37	0.021	0.05	0.51	35%	27%	426,737	
NMC (111)	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6%		0	
NMC (532)	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00	33%		0	
NMC (442)	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0	
NMC (811)	megaton	0.00	0.00	0.06	0.59	0.073	0.092	1.10	7%	58%	916,695	
NMC (622)	megaton	0.00	0.00	0.02	0.07	0.023	0.014	0.15	13%	8%	126,441	
LFP	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0	
Total	**megaton**	**0.011**	**0.000**	**0.086**	**1.105**	**0.132**	**0.169**	**1.897**	100%	100%	1,580,509	85.4%
Consumer electronics												
LCO	megaton	0.00	0.00	0.00	0.00	0.12	0.01	0.16	100%	100%	133,199	
Total	**megaton**	**0.000**	**0.000**	**0.000**	**0.000**	**0.120**	**0.015**	**0.160**	100%	100%	133,199	7.2%
StatioNAry storage												
NCA	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0	
NCA+	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0	
NMC (111)	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00	35%		0	
NMC (532)	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0	
NMC (442)	megaton	0.00	0.00	0.007	0.008	0.004	0.0023	0.028	20%	17%	23,376	
NMC (811)	megaton	0.00	0.00	0.0018	0.017	0.00	0.00	0.03		19%	26,126	
NMC (622)	megaton	0.00	0.00	0.0068	0.022	0.0072	0.0044	0.048	15%	29%	39,877	
LFP	megaton	0.00	0.032	0.00	0.00	0.00	0.0039	0.06	30%	35%	48,127	
Total	**megaton**	**0.000**	**0.032**	**0.016**	**0.046**	**0.013**	**0.013**	**0.165**	100%	100%	137,505	7.4%
Summary												
Grand Total Required	megaton	0.011	0.032	0.102	1.151	0.265	0.197	2.221			1,851,213	100%
Total Material Available	megaton	30,000	170	760	89	7	14	300				
Available factor (Available/Required)	-	NA	NA	NA	NA	NA	NA	NA				
Maximum capacity available											**NA**	

Metals		Aluminium	Iron	Manganese	Nickel	Cobalt	Lithium	NAtural Graphite	Expected chemistry		Capacity forecast 2050	
Symbols		Al	Fe	Mn	Ni	Co	Li		2020	2030, 2040 2050	MWh	Share of each category
Required material												
Passenger electric vehicles (EVs) (including e-busses)												
NCA	megaton	0.8946	0.00	0.00	31.76	5.815	4.920	53.67	6%	7%	44,729,072	
NCA+	megaton	3.4505	0.00	0.00	150.10	8.626	20.70	207.03	35%	27%	172,526,419	
NMC (111)	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6%		0	
NMC (532)	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00	33%		0	
NMC (442)	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0	
NMC (811)	megaton	0.00	0.00	25.94	237.19	29.649	37.061	444.73	7%	58%	370,612,308	
NMC (622)	megaton	0.00	0.00	8.69	27.60	9.201	5.623	61.34	13%	8%	51,118,939	
LFP	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0	
Total	**megaton**	**4.345**	**0.000**	**34.633**	**446.652**	**53.291**	**68.308**	**766.784**	100%	100%	638,986,739	94.4%
Consumer electronics												
LCO	megaton	0.00	0.00	0.00	0.00	0.48	0.06	0.64	100%	100%	535,635	
Total	**megaton**	**0.000**	**0.000**	**0.000**	**0.000**	**0.482**	**0.059**	**0.643**	100%	100%	535,635	0.1%
StatioNAry storage												
NCA	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0	
NCA+	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0	
NMC (111)	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00	35%		0	
NMC (532)	megaton	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0	
NMC (442)	megaton	0.00	0.00	2.018	2.144	1.072	0.6307	7.569	20%	17%	6,307,227	
NMC (811)	megaton	0.00	0.00	0.4934	4.512	0.56	0.70	8.46		19%	7,049,253	
NMC (622)	megaton	0.00	0.00	1.8291	5.810	1.9367	1.1835	12.911	15%	29%	10,759,387	
LFP	megaton	0.00	8.700	0.00	0.00	0.00	1.0388	15.58	30%	35%	12,985,467	
Total	**megaton**	**0.000**	**8.700**	**4.341**	**12.466**	**3.573**	**3.558**	**44.522**	100%	100%	37,101,333	5.5%
Summary												
Grand Total Required	megaton	4.345	8.700	38.974	459.118	57.346	71.925	811.948			676,623,707	100%
Total Material Available	megaton	30,000	170	760	89	7	14	300				
Available factor (Available/Required)	-	NA	NA	NA	0.19	0.12	0.19	0.37				
Maximum capacity available											**81,412,289**	

B Levelized cost of storage calculations for 10 other technologies (low decrease scenario)

		Pumped Hydro Storage				Compressed Air Energy Storage			
Year		2020	2030	2040	2050	2020	2030	2040	2050
Charging									
Charging time	hours	4	4	4	4	4	4	4	4
C-rate		0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Charging time	days	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Required charging and discharging power	kW th	250	250	250	250	250	250	250	250
Storage capacity	MWh	1	1	1	1	1	1	1	1
Annual charging times	#/year	365	365	365	365	365	365	365	365
Round trip efficiency	%	75%	85%	85%	85%	42%	60%	60%	60%
Annual discharging capacity	MWh/year	316	337	337	337	237	283	283	283
Investment parameters									
Lifetime	years	60	60	60	60	40	40	40	40
Weighted average cost of capital	%	8%	8%	8%	8%	8%	8%	8%	8%
Annuity factor		0.081	0.081	0.081	0.081	0.084	0.084	0.084	0.084
Balance of plant (BOP) factor		1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Charging and discharging									
Capex	USD/kW	1500	1,350	1,215	1,094	1000	900	810	729
Capex	USD	450,000	405,000	364,500	328,050	300,000	270,000	243,000	218,700
Annual capex	USD/year	36,359	32,723	29,451	26,506	25,158	22,642	20,378	18,340
Fixed O&M (Operation and Maintenance)	USD/kW/year	3	3	3	3	20	20	20	20
Annual FOM (Fixed O&M) costs	USD/year	750	750	750	750	5000	5000	5000	5000
Storage									
Capex	USD/kWh	20	15	11	8	120	90	68	51
Capex	USD	24,000	18,000	13,500	10,125	144,000	108,000	81,000	60,750
Annual capex	USD/year	1,939	1,454	1,091	818	12,076	9,057	6,793	5,095
Fixed O&M	% of investment/year	3.0%	3.0%	3.0%	3.0%	5.0%	5.0%	5.0%	5.0%
Fixed O&M	USD/kWh/year	0.6	0.5	0.3	0.3	6.0	4.5	3.4	2.5
Annual FOM costs	USD/year	600	450	338	253	6,000	4,500	3,375	2,531
Total costs	USD/year	39,648	29,924	22,630	17,160	48,234	37,425	29,319	23,239
Levelized cost of storage (LCOS)	**USD/MWh**	**125**	**106**	**96**	**86**	**204**	**155**	**142**	**129**

		Liquid Air Energy Storage				Lead-acid Battery			
Year		2020	2030	2040	2050	2020	2030	2040	2050
Charging									
Charging time	hours	4	4	4	4	4	4	4	4
C-rate		0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Charging time	days	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Required charging and discharging power	kW th	250	250	250	250	250	250	250	250
Storage capacity	MWh	1	1	1	1	1	1	1	1
Annual charging times	#/year	365	365	365	365	365	365	365	365
Round trip efficiency	%	70%	80%	80%	80%	75%	85%	85%	85%
Annual discharging capacity	MWh/year	305	326	326	326	316	337	337	337
Investment parameters									
Lifetime	years	40	40	40	40	15	15	15	15
Weighted average cost of capital	%	8%	8%	8%	8%	8%	8%	8%	8%
Annuity factor		0.084	0.084	0.084	0.084	0.117	0.117	0.117	0.117
Balance of plant (BOP) factor		1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Charging and discharging									
Capex	USD/kW	1900	1710	1539	1385	600	540	486	437
Capex	USD	570,000	513,000	461,700	415,530	180,000	162,000	145,800	131,220
Annual capex	USD/year	47,800	43,020	38,718	34,846	21,029	18,926	17,034	15,330
Fixed O&M (Operation and Maintenance)	USD/kW/year					50	50	50	50
Annual FOM (Fixed O&M) costs	USD/year					12500	12500	12500	12500
Storage									
Capex, storage	USD/kWh	530	477	429	386	400	360	324	292
Capex, project	USD	636,000	572,400	515,160	463,644	480,000	432,000	388,800	349,920
Annual capex	USD/year	53,335	48,002	43,201	38,881	56,078	50,470	45,423	40,881
Fixed O&M	% of investment/year								
Fixed O&M	USD/kWh/year								
Annual FOM costs	USD/year								
Total costs	USD/year	101,135	75,852	56,889	42,666	89,607	70,331	55,873	45,030
Levelized cost of storage (LCOS)	**USD/MWh**	**331**	**279**	**251**	**226**	**283**	**243**	**223**	**204**

		Sodium Sulphur Battery				Nickel Cadmium Battery			
Year		2020	2030	2040	2050	2020	2030	2040	2050
Charging									
Charging time	hours	4	4	4	4	4	4	4	4
C-rate		0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Charging time	days	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Required charging and discharging power	kW th	250	250	250	250	250	250	250	250
Storage capacity	MWh	1	1	1	1	1	1	1	1
Annual charging times	#/year	365	365	365	365	365	365	365	365
Round trip efficiency	%	80%	90%	90%	90%	75%	85%	85%	85%
Annual discharging capacity	MWh/year	326	346	346	346	316	337	337	337
Investment parameters									
Lifetime	years	15	15	15	15	20	20	20	20
Weighted average cost of capital	%	8%	8%	8%	8%	8%	8%	8%	8%
Annuity factor		0.117	0.117	0.117	0.117	0.102	0.102	0.102	0.102
Balance of plant (BOP) factor		1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Charging and discharging									
Capex	USD/kW	3000	2700	2430	2187	1500	1350	1215	1094
Capex	USD	900,000	810,000	729,000	656,100	450,000	405,000	364,500	328,050
Annual capex	USD/year	105,147	94,632	85,169	76,652	45,833	41,250	37,125	33,413
Fixed O&M (Operation and Maintenance)	USD/kW/year	80	80	80	80	20	20	20	20
Annual FOM (Fixed O&M) costs	USD/year	20000	20000	20000	20000	5000	5000	5000	5000
Storage									
Capex	USD/kWh	500	450	405	365	2,400	2160	1,944	1,750
Capex	USD	600,000	540,000	486,000	437,400	2,880,000	2,592,000	2,332,800	2,099,520
Annual capex	USD/year	70,098	63,088	56,779	51,101	293,334	264,001	237,601	213,841
Fixed O&M	% of investment/year								
Fixed O&M	USD/kWh/year								
Annual FOM costs	USD/year								
Total costs	USD/year	195,244	151,433	118,575	93,931	344,168	259,376	195,782	148,086
Levelized cost of storage (LCOS)	**USD/MWh**	**598**	**513**	**468**	**427**	**1089**	**922**	**831**	**750**

		Vanadium Redox Flow Battery				Polysulfide Bromide Flow Battery			
Year		2020	2030	2040	2050	2020	2030	2040	2050
Charging									
Charging time	hours	4	4	4	4	4	4	4	4
C-rate		0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Charging time	days	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Required charging and discharging power	kW th	250	250	250	250	250	250	250	250
Storage capacity	MWh	1	1	1	1	1	1	1	1
Annual charging times	#/year	365	365	365	365	365	365	365	365
Round trip efficiency	%	70%	80%	80%	80%	70%	80%	80%	80%
Annual discharging capacity	MWh/year	305	326	326	326	305	326	326	326
Investment parameters									
Lifetime	years	20	20	20	20	15	15	15	15
Weighted average cost of capital	%	8%	8%	8%	8%	8%	8%	8%	8%
Annuity factor		0.102	0.102	0.102	0.102	0.117	0.117	0.117	0.117
Balance of plant (BOP) factor		1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Charging and discharging									
Capex	USD/kW	1500	1350	1215	1093.5	2500	2250	2025	1823
Capex	USD	450,000	405,000	364,500	328,050	750,000	675,000	607,500	546,750
Annual capex	USD/year	45,833	41,250	37,125	33,413	87,622	78,860	70,974	63,877
Fixed O&M (Operation and Maintenance)	USD/kW/year	70	70	70	70				
Annual FOM (Fixed O&M) costs	USD/year	17500	17500	17500	17500				
Storage									
Capex	USD/kWh	1,000	900	810	729	1,000	900	810	729
Capex	USD	1,200,000	1,080,000	972,000	874,800	1,200,000	1,080,000	972,000	874,800
Annual capex	USD/year	122,223	110,000	99,000	89,100	140,195	126,176	113,558	102,202
Fixed O&M	% of investment/year								
Fixed O&M	USD/kWh/year								
Annual FOM costs	USD/year								
Total costs	USD/year	185,556	168,751	153,625	140,013	227,818	205,036	184,532	166,079
Levelized cost of storage (LCOS)	**USD/MWh**	**608**	**517**	**471**	**429**	**746**	**628**	**565**	**509**

		Supercapacitors				Superconducting Magnetic Energy Storage			
Year		2020	2030	2040	2050	2020	2030	2040	2050
Charging									
Charging time	hours	4	4	4	4	4	4	4	4
C-rate		0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Charging time	days	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Required charging and discharging power	kW th	250	250	250	250	250	250	250	250
Storage capacity	MWh	1	1	1	1	1	1	1	1
Annual charging times	#/year	365	365	365	365	365	365	365	365
Round trip efficiency	%	95%	95%	95%	95%	95%	95%	95%	95%
Annual discharging capacity	MWh/year	356	356	356	356	356	356	356	356
Investment parameters									
Lifetime	years	30	30	30	30	25	25	25	25
Weighted average cost of capital	%	8%	8%	8%	8%	8%	8%	8%	8%
Annuity factor		0.089	0.089	0.089	0.089	0.094	0.094	0.094	0.094
Balance of plant (BOP) factor		1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Charging and discharging									
Capex	USD/kW	400	360	324	291.6	489	440.1	396.09	356
Capex	USD	120,000	108,000	97,200	87,480	146,700	132,030	118,827	106,944
Annual capex	USD/year	10,659	9,593	8,634	7,771	13,743	12,368	11,132	10,018
Fixed O&M (Operation and Maintenance)	USD/kW/year	6	6	6	6	18.5	18.5	18.5	18.5
Annual FOM (Fixed O&M) costs	USD/year	1500	1500	1500	1500	4625	4625	4625	4625
Storage									
Capex	USD/kWh	2,000	1800	1,620	1,458	10,000	9000	8,100	7,290
Capex	USD	2,400,000	2,160,000	1,944,000	1,749,600	12,000,000	10,800,000	9,720,000	8,748,000
Annual capex	USD/year	213,186	191,867	172,681	155,412	1,124,145	1,011,731	910,558	819,502
Fixed O&M	% of investment/year								
Fixed O&M	USD/kWh/year								
Annual FOM costs	USD/year								
Total costs	USD/year	225,345	202,961	182,815	164,683	1,142,513	1,028,724	926,314	834,145
Levelized cost of storage (LCOS)	**USD/MWh**	**633**	**571**	**514**	**463**	**3211**	**2892**	**2604**	**2345**